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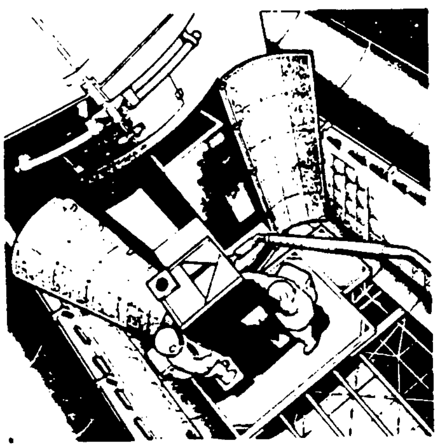
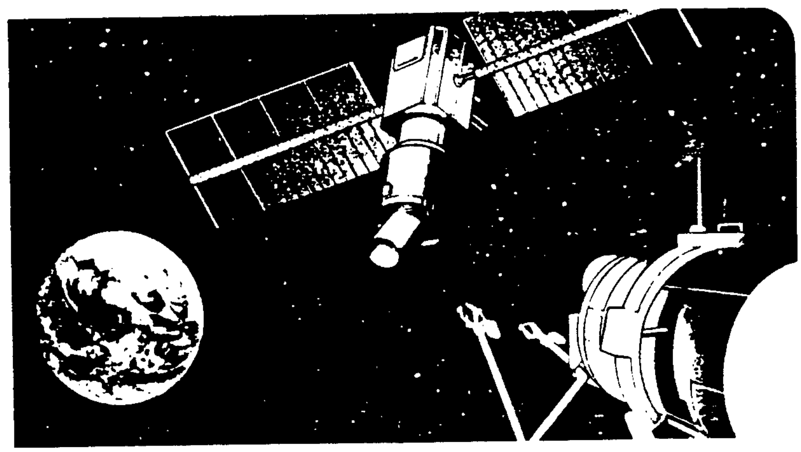
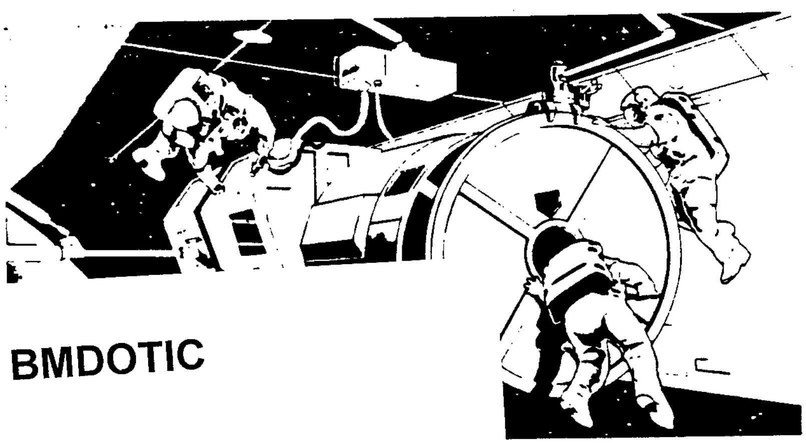
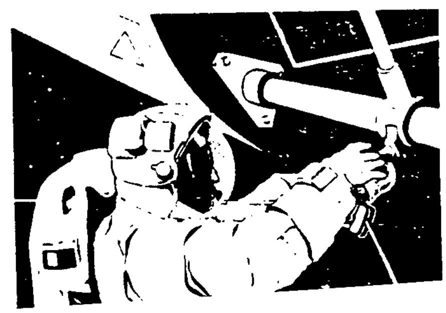
Space Assembly, Maintenance and Servicing Study









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VOLUME V: Simulation Report

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SAMS STUDY FINAL REPORT

VOLUME V

SIMULATION REPORT

INDEX TO VOLUMES

FOREWARD

This Space Assembly, Maintenance, Servicing (SAMS) Study final report is submitted by Lockheed Missiles and Space Company in response to SAMS Study CDRL-027A2 per contract number F04701-86-C-0030.

This document is divided into the following five volumes:

Volume I	Executive Summary
Volume II	System Analysis
Volume III	Design Concepts
Volume IV	Concept Development Plan
Volume V	Simulation Report

The Simulation Report section, Volume V, contains the following sections:

Section 1.0	Introduction
Section 2.0	Neutral Buoyancy Simulations
Section 3.0	Robotics Simulations
Section 4.0	Conclusions and Design Recommendations

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APPROVED ______________________

Carl D. Patterson
SAMS Study Program
Manager

SAMS STUDY FINAL REPORT VOLUME V

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ACRONYMS

AEC	
AI	Artificial Intelligence
ASE	Airborn Support Equipment
B&W	Black and White
CRT	Cathode Ray Tube
CSTS	Current and SAMS Technology Simulations
DIU	Data Interface Unit
DMU	Data Management Unit
DoD	Department of Defense
DRM	Design Reference Mission
ED	Electronic Documentation
EDTG	Electronic Documentation Test Group
EMU	Extra Vehicular Mobility Unit
ES	Equipment Section
EVA	Extra Vehicular Activity
F3	Form, Fit, and Functional
FGE	Fine Guidance Electronics
FSS	Flight Support System
GEO	Geosynchronous Earth Orbit
GFD	Government Furnished Data
HMD	Helmet Mounted Display
HST	Hubble Space Telescope
IEO	Intermediate Earth Orbit
IVA	Intravehicular Activity
JSC	Johnson Space Center
LEASAT	Lease Craft Satellite
LCD	Liquid Crystal Display
LEO	Low Earth Orbit
LMSC	Lockheed Missiles & Space Company, Inc.
m	Meter
M&R	Maintenance and Refurbishment
MAT	Multiple Access Transponder
MDAC	McDonnell Douglas Astronautics Company
MLI	Multilayer Insulation

MMD	Mean Mission Duration
MMV	Manned Maneuvering Unit
MOTV	Manned Orbital Transfer Vehicle
MSE	Manned Spaceflight Engineer
NASA	National Aeronautics and Space Administration
NB	Neutral Buoyancy
NROSS	Navy Remote Ocean Sensing System
NRU	Non Replacable Unit
OMV	Orbital Maneuvering Unit
OPS	Operations
ORS	Orbital Refueling System
ORU	Orbital Replaceable Unit
OTS	Orbital Transfer System
OTV	Orbital Transfer Vehicle
PDU	Power Distribution Unit
PFR	Portable Foot Restraint
POC	Proof of Concept
POCC	Payload Operation Control Center
PRD	Payload Retention Devices
PROXOPS	Proximity Operations
RMS	Remote Manipulator System
S/C	Spacecraft
SAMS	Space Assembly, Maintenance, and Servicing
SDIO	Strategic Defense Initiative Office
SPTG	Standard Procedure Test Group
SS	Space Station
ST	Space Telescope
STAS	Space Transportation Architefcture Study
SV	Satellite Vehicle
TPC	Total Program Cost
TR	Tape Recorder
TTG	Training Test Group
USAF	United States Air Force
UWTF	Underwater Test Facility
VIMAD	Voice Interactive Maintenance Aiding Device
WBS	Work Breakdown Structure

1.0 Introduction

The Space Assembly, Maintenance, and Servicing (SAMS) study manned simulation activity was designed to evaluate and demonstrate selected hardware, tools, and operations concepts which promise significant improvements over current technology in the areas of space assembly, maintenance, and servicing. This report documents two manned neutral buoyancy tests and a mini-series of three robotics tests performed by the Lockheed team in support of the SAMS study contract.

The primary thrust of the first neutral buoyancy test was related to EVA tools and operations concepts. The results apply equally to the three SAMS missions - Assembly, Maintenance, and Servicing. The principal objective of this test was to evaluate, under simulated EVA conditions, an electronic documentation system designed to lead a generically EVA-trained astronaut through a complex EVA servicing task with which he had no previous training. Two separate electronic information management systems were evaluated. The system used for the primary data runs, developed by Lockheed, was based on video tape. The second system, known as the Voice Interactive Maintenance Aiding Device (VIMAD), was developed by Honeywell. It was based on a laser disk. Both systems provided video and audio signals to a Helmet Mounted Display (HMD) developed by Carnegie-Melon University. The known EVA task selected as a basis for evaluating the electronic information management systems was the Orbital Refueling System (ORS) hydrazine transfer experiment flown on STS-41G. This test marked the first known time that a HMD and an associated electronic information management system have been used on a space suit in an actual neutral buoyancy test. This test produced a comparison of task performance by test subjects familar with the task and performing from memory, with performance by equally experienced subjects unfamiliar with the task and relying on instructions provided by the electronic documentation system.

In addition to the primary test, three space assembly technology experiments were conducted on a time-available basis. Hardware items for these evaluations were provided by ILC-Dover, ILC-Houston, and the Able Engineering Company.

This test was conducted in the McDonnell-Douglas Underwater Test Facility (UWTF) in Huntington Beach, CA, during 4 days of suited operations in early February 1987.

The thrust of the second neutral buoyancy test was also related to EVA tools. The results are primarily applicable to maintenance aspects of SAMS missions. The first objective of this test was to evaluate EVA changeout of 5 current technology ORU's, using a new set of NASA developed EVA hand tools. The second major objective was to evaluate EVA changeout of a new modular ORU concept which is also robot-compatible. The modular ORU was evaluated in two sizes; the largest was a trapezoidally shaped box whose major dimensions were 54.0" x 38.1" x 18.4", of mass equivalent to 1100 lbs.

A second generation version of the Orbital Refueling System electronic documentation system procedures tape used during the first neutral buoyancy test was also evaluated on a time-available basis during this experiment.

The second neutral buoyancy test was conducted in the McDonnell-Douglas UWTF during 10 days of suited testing beginning in mid-March, 1987.

All hardware elements for both neutral buoyancy test series were thoroughly evaluated by at least one of two experienced Lockheed EVA test crewmembers. A number of USAF MSE's also participated in each test series.

The objective of the robotics tests was to evaluate robot performance in a series of human-robot interaction tasks which are representative of functions inherent in most servicing operations. Tests performed in this series included robotic retrieval of a specific tool from a tool board and holding it at a prescribed position; replacing a tool in a tool board after being handed the tool by an astronaut, sensing an astronauts hand position and handing a specific tool directly to the hand location, and working in parallel with an astronaut to remove and replace an ORU from a rack. For this latter task, the robot sensed the force inputs of the astronaut and duplicated them on a parallel handhold.

The rototics tests were performed in the Robotics Institute at Carnegie-Melon University, Pittsburgh, PA.

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2.0 NEUTRAL BUOYANCY SIMULATIONS

2.1 OBJECTIVES

2.1.1 Test 1:

Test 1 was divided into two experiments. The prime experiment was the evaluation of EVA application of electronic data management systems. The secondary experiment was a three part evaluation of EVA assembly technology.

The primary objective of the first neutral buoyancy experiment was to evaluate an electronic data management system and associated crewmember display as a means of enhancing EVA crewmember performance and/or reducing EVA crewmember training time. Specific sub-element objectives were:

- o Evaluate one or more concepts for displaying electronic information to a suited astronaut.
- o Demonstrate simulated voice control for management and retrieval of system information.
- o Evaluate the potential for either improving EVA crewmember performance or markedly reducing EVA crewmember training time.
- o Evaluate impact to IVA and EVA crew communications.
- o Establish timeline and procedural data base for evaluating future manned space flight engineer neutral buoyancy simulations.

The objective of the first assembly technology experiment was to evaluate a new lock assembly concept for attaching struts to nodes during the on-orbit buildup of an erectable structure. Specific sub-element objectives were:

- o Evaluate glove/strut interface characteristics.
- o Evaluate strut installation and release operations.

The objective of the second assembly technology experiment was to evaluate techniques for installing insulation blankets on large space structures. Specific sub-element objectives were:

- o Evaluate an unrestrained two person manual blanket deployment technique.
- o Evaluate 3 blanket-to-truss attachment concepts.

The objective of the third assembly technology experiment was to evaluate the deployment and operation of a one piece environmental enclosure.

Specific sub-element objectives were:

- o Evaluate a two person manual deployment concept.
- o Evaluate a manually operated winch as an aid to deploying the enclosure and restraining it until the attachments to adjacent strut structure were complete.
- o Evaluate crew operations required to open and close the enclosure entrance door.
- o Evaluate crew entry/exit from the enclosure.
- o Evaluate crew translation along one internal edge of the enclosure.

2.1.2 Test 2:

There were two objectives of the second neutral buoyancy test series. The first was to perform detailed evaluations of 5 representative current technology ORU's, using current technology EVA handtools, to provide a basis for development of EVA handtool requirements for the early SAMS epoch. The emphasis in this investigation was on "generic task realism", i.e., the objective was to ensure that the task used for each specific tool evaluation was realistic. For this reason, dimensionally accurate mockups were fabricated of ORU's from an actual spacecraft program, with attention to connector types, spacing, orientation and pin loading. These ORU mockups were generically placed in a mockup of two spacecraft equipment bays. The objective was to represent typical mounting situations which are encountered in actual spacecraft, rather than to look at access limitations which are peculiar to a particular spacecraft.

The second major objective of the second neutral buoyancy test series was to perform a preliminary crew interface evaluation of a new ORU mounting concept, known as the "sword and scabbard", developed by Lockheed for the SAMS Study.

The concept integrates the installation alignment aids, the mechanical mounting interfaces, and the electrical interfaces so that the crewmember is required to manually position and align the ORU to start into the alignment guide, push the ORU down the guide to the fully installed position, and then use a tool on a single mechanical connector to secure the ORU to the spacecraft.

Specific sub-objectives of this task included:

(1) Determining the acceptable range for foot restraint height with respect to the ORU mounting interface location, and the preferred foot restraint height, for the following test conditions:

- o Large ORU; sword and scabbard centrally mounted on one side.
- o Small ORU; sword and scabbard centrally mounted on one side.
- o Small ORU; sword and scabbard centrally mounted on top of the ORU.
- o Small ORU; sword and scabbard centrally mounted on the bottom of the ORU.

(2) Determining handhold requirements on the ORU to facilitate manual handling and positioning for installation. Of particular interest was examination of any requirements for handholds mounted on ORU surfaces other than the front face.

(3) Evaluating the operation of the blade and scabbard concept as represented by the first generation mockup, with respect to pre-installation ORU positioning requirements, entry ramp angles, blade and scabbard clearances and alignment pin geometry.

2.2 FACILITY AND TEST HARDWARE

The facility for both neutral buoyancy tests was the McDonnell-Douglas Underwater Test Facility (UWTF) at Huntington Beach, California. The UWTF is a 70' diameter by 35' deep, covered, in-gound neutral buoyancy facility with extensive audiovisual monitoring and recording capabilities, and provisions for simultaneous operations by two space shuttle extravehicular mobility units (EMU's).

2.2.1 Test 1:

The test-unique hardware equipment items, listed by supplier developer, were the following:

NASA JSC:

- o One (1) STS-41G Orbital Refueling System (ORS) neutral buoyancy crew trainer, including the following tools:
  - ball valve housing
  - cap retainer
  - dust cap removal
  - multipurpose tool
  - nut retainer assemby
  - retrieval tool
  - seal verification tool
  - spanner
  - wire clippers

LMSC:

- o One (1) multipurpose test stand
- o Two (2) multipurpose test stand extensions
- o One (1) ORS to test stand interface adapter
- o One (1) single node test stand and attached foot restraint
- o One (1) multipurpose test stand to 5m bay cruciform interface adapter
- o Four (4) test stand nodes
- o Two (2) 5m bays of erectable truss
- o One (1) ORS procedures video tape

CMU:

- One (1) Black and White (B&W) Helmet Mounted Display system

Honeywell:

- One (1) VIMAD system
- One (1) ORS procedures laser disc

ILC:

- One (1) multilayer insulation (MLI) blanket dispenser
- Five (5) MLI blanket mockups (neutrally buoyant mesh)
- Two (2) wrist tethers
- One (1) 5m environmental enclosure (neutrally buoyant mesh)
- Two (2) EVA winches

ABLE ENGINEERING COMPANY (AEC)

- One (1) AEC erectable structure node
- Eight (8) AEC neutrally buoyant short struts and lock assemblies

The Electronic Documentation Test Hardware (Fig. 2-1) used during the LMSC simulations utilized a Helmet Mounted Display (HMD) that consisted a small CRT, a mirror held at the appropriate angle and the surrounding structure and shroud. Data was supplied to the HMD by a Video Cassette Recorder with freeze frame capability via a 100' waterproof line.

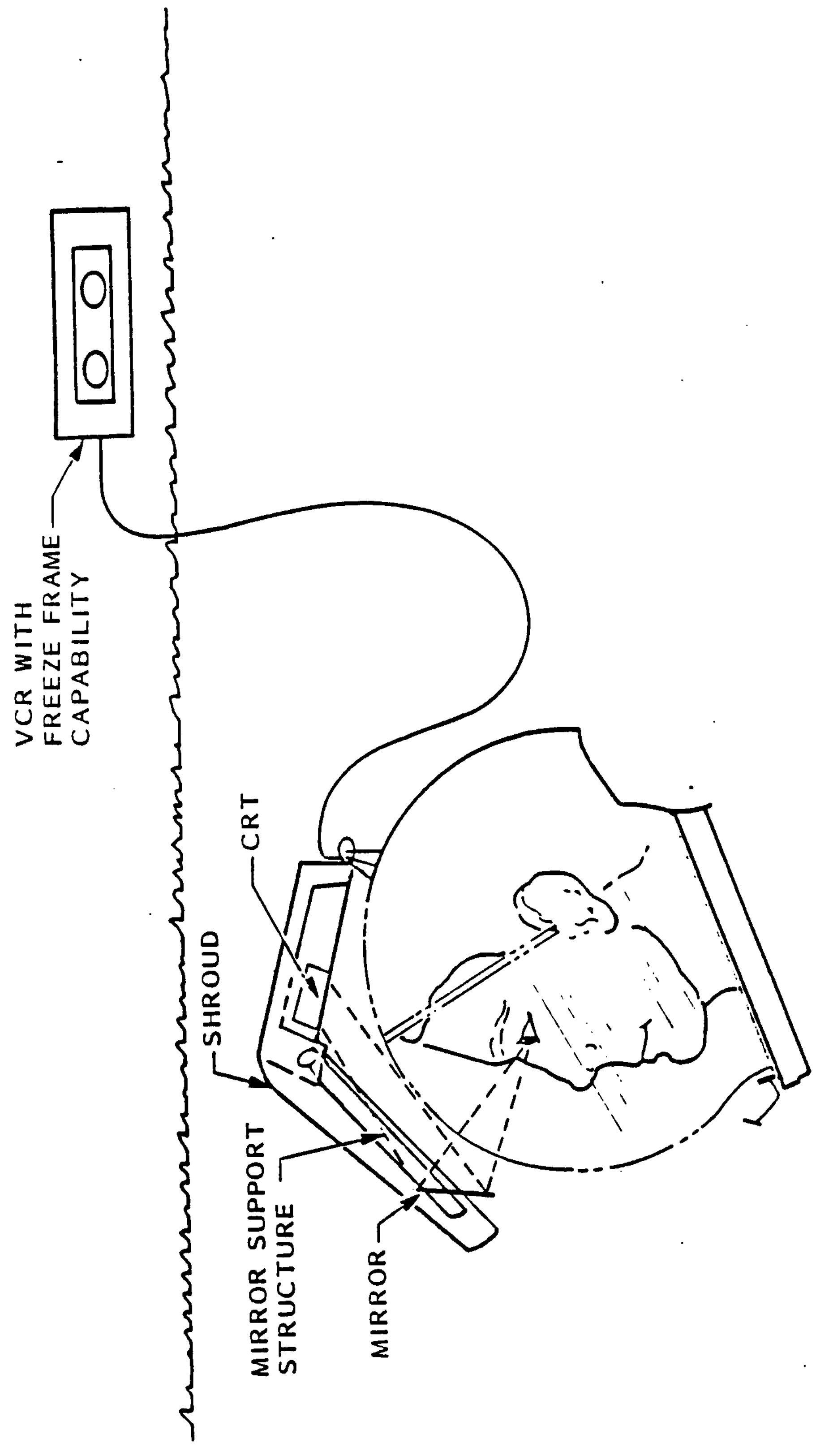

Fig. 2-1 Electronic Documentation Test Hardware

2.2.2 Test 2:

The test-unique hardware equipment items listed by supplier or developer, were the following:

LMSC:

- o A representative spacecraft equipment section including 3 bays; two equipped with functional doors and latches.
- o Five (5) common adapter plates allowing mounting of ORU's internally in the bays, or on the bay doors.
- o One (1) LMSC multipurpose support stand and 2 foot restraint adapters.
- o Two (2) stand extensions
- o Five (5) representative current technology ORU's.
- o Two (2) SAMS technology ORU's with multiple crew interface mounting provisions.

USAF:

- o Two (2) Portable EVA foot restraints.

NASA JSC:

- o EVA handtools required for the current technology ORU changeouts, including:

- Hex Coax Connector Tool
- Shrouded Flex Screwdriver
- "D" Connector Demate Tool
- "D" Connector Mate Tool
- 5/16" Rigid Hex Capture Tool W/10.3" Extension
- Adjustable Door Stay
- 3/8" Drive McTether Ratchet
- Equipment Tether, 34"
- Ratchet McCaddy

NASA JSC (CONTINUED)

- Standard McCaddy
- Waist Tether
- Wrist Tether
- Mini-Work Station
- Torque-Set Tip Tool #10 Assembly
- 90 deg Circular Connector Tool
- Trash Bag, Large W/Lips
- Electrical Connector Pin Straightener
- Trash Bag, Small
- 0 deg Circular Connector Tool
- Rigid Hex Capture Tool W/10.3" Extenion
- 5/16" Wobble Hex Capture Tool 10.3" Extension
- Leasat Connector Tool

NASA MSFC

- o EVA handtools required for the current technology ORU changeouts, including:
  - 7/16" Sock. 6" Extension
  - 7/16" Sock. 12" Extension
  - 9.0 Ft-lb Torque Limiter
- o Portable foot restraint
- o Portable ORU Handle, Small
- o Portable ORU Handle, Large

The LMSC SAMS ORU was designed to utilize a single interface attachment mechanism known as the "sword and scabbard". The intent of such a mechanism is to provide the ORU with the required structural, electrical and fluid interfaces with one attachment, eliminating a great deal of the EVA crewmember workload and providing an interface system workable by remote servicing systems. The "sword" is a blade mounted to the ORU tapered at the end designed to interface with the "scabbard", a channel mounted on the spacecraft. Electrical and/or fluid interfaces are on two facing plates integral to the system.

The ORU itself, as depicted in Fig. 2-2 was designed to simulate two sizes of flight ORUs, one large enough to fill an entire bay of the CSTS hardware and a smaller version, attained by the removal of two sections. The attachment system was designed to be tested in three different positions, mounted on the side of the bay, the top of the bay, and the bottom of the bay. The full size ORU could only be operated with the interface mounted in the side position.

The ORU was also designed with two sets of handholds included in the experiment to determine their usefulness. One pair of handholds was mounted to the outer face of unit (see Fig. 2-2) and the other pair was mounted in a recessed position on the left side of the ORU. To aid visual cues, the "sword" was painted red and the "scabbard" was painted yellow versus the basic grey of the main structure and white of the ORU itself.

During simulation runs, the Portable Foot Restraint (PFR) was mounted to the left side of the ORU bay to facilitate the removal and installation of the ORU. During the simulation of the bottom mounted interface, however, the PFR was mounted directly below the bay.

2.3 SIMULATION CHRONOLOGY AND RESULTS

The distribution of daily test activity among the experiments is listed in Table 2-3. The remainder of this section summaries each day's test activity.

2.3.1 Test 1:

Day 1: Setup and checkout of the EMU's and umbilicals occupied the full day. No suited test runs were attempted.

The integration and checkout of the electronic documentation system equipment the Honeywell-supplied Voice Interactive Maintenance Aiding Device (VIMAD) and

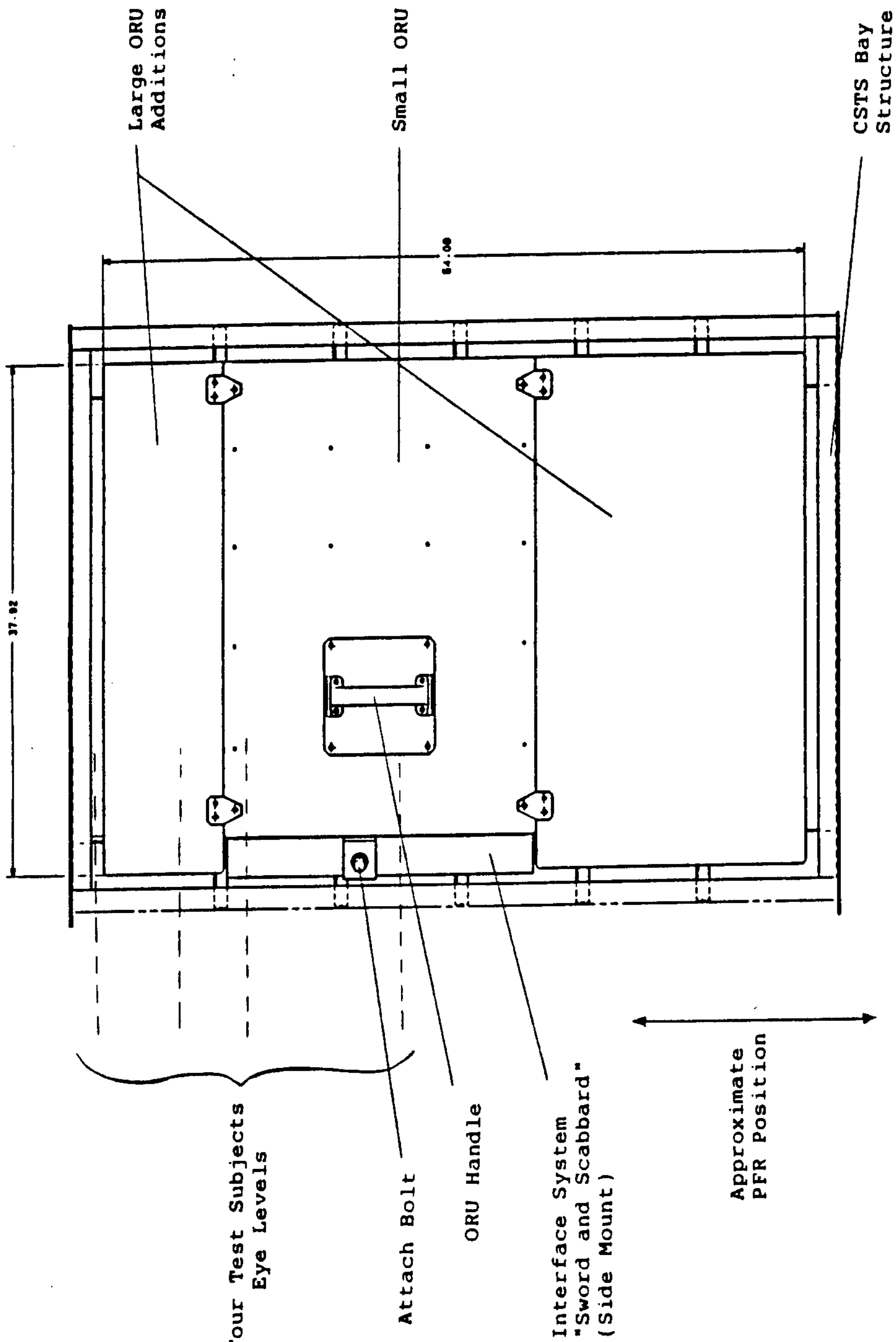

Fig. 2-2 SAMS Technology ORU

EXPERIMENT	TUES. 3 FEBRUARY AM	PM	WED. 4 FEBRUARY AM	PM	THURS. 5 FEBRUARY AM	PM	FRI. 6 FEBRUARY AM	PM
ELECTRONIC	LMSC	LMSC		USAF	USAF	USAF	USAF	USAF
DOCUMENTATION				USAF	USAF	USAF	USAF	
AEC LOGIC	LMSC							
ASSEMBLY								
THERMAL			LMSC	USAF				
COVERS								
ENVIRONMENTAL	LMSC							
ENCLOSURE								

Table 2-1 Distrubution of Runs For the First Neutral Buoyancy

associated laser disc-based ORS procedures, the Carnegie-Mellon University (CMU) Helmet Mounted Display (HMD), and the LMSC-produced ORS procudures video tape played on UWTF equipment revealed synchronization instabilities resulting from the long signal line lengths and multiple connections. The result was substantial signal degradation as viewed both on the HMD and on the control room monitors. In addition, apparant HMD clarity was further distorted by numerous scratches present in the helmet which were amplified by glare from stray light.

Day 2: EMU operations were scheduled in parallel to initiate assembly technology experiment operations with one of the LMSC test crewmembers while the other continued to work with the HMD and the associated electronic system.

By the end of Day 2, based on two suited ORS exploratory dives, an electronic system was selected for the ORS runs, consisting of the CMU-developed single mirror, 4" B&W Sony CRT-based HMD and the LMSC-developed ORS procedures video tape played by a UWTF control room recorder and special effects generator. For the MSE data runs the system was operated by one of the Lockheed EVA test crewmembers simulating voice control. The options evaluated in selecting this test configuration included various combinations of CRT and Liquid Crystal Display (LCD) based HMD's, various HMD mirror combinations (half silvered, 60% silvered, full silvered, single and two mirror combinations), and two interpretations of how to present the ORS procedures to the subject (one produced by Honeywell on laser disk, the other by LMSC on video tape). In addition, the AEC erectable structure lock assembly evaluation and 4 of the 5 environmental enclosure evaluation objectives were completed.

Day 3: The thermal blanket installation test was completed by both LMSC crewmembers working together.

The first experiment test run (the ORS procedure by a trained subject) was performed by a USAF subject. Two USAF subjects then performed the thermal blanket deployment test, and the second USAF subject then completed the second primary experiment run (the ORS procedure performed by an untrained subject using the electronic documentation system).

Day 4: Four experiment runs were conducted using USAF subjects. The final run was truncated slightly due to slow performance by the subject and lack of time at day's end.

Day 5: Three experiment runs were performed, including one "double run" by a USAF electronic subject to permit a back-to-back comparison of both the Lockheed and the Honeywell versions of the ORS instructional procedures.

2.3.2 Test 2:

The second neutral buoyancy test series included 10 days of suited operations. The distribution of daily test activity is summarized in Tables 2-2 and 2-3.

During the first week of simulations, the SAMS designed ORU remained in the large ORU configuration and was cycled by several test subjects. The results of these runs are summarized in the overall conclusions and recommendations section. The tests during this period began with the loosening of the attach bolt with the proper size socket and ratchet. The ORU was then cycled in and out of the interface mechanism several times by each subject while their comments and suggestions were recorded. All subjects utilized essentially the same foot restraint position all week.

Monday and Tuesday of the second week of simulations a series of detailed tests with the ORU system were performed. Monday, four foot restraint positions were tried, and each removal and insertion cycle were timed, all with the large configuration ORU. Each test was run four times, each with a different viewing angle from the swim camera. Tuesday, the small configuration ORU was used with the same foot restraint positions as Monday's tests. The two other interface positions were also tried, one at the bottom of the CSTS bay and one at the top of the bay, both with the small ORU.

The data from these runs is presented in Table 2-4. Foot restraint position is defined by the vertical distance of the subject's eyes from the attach bolt of the ORU interface system. This measurement determines sighting angles for

Table 2-2 DISTRIBUTION OF TEST RUNS SAMS TEST #2, WEEK 1

BAY	EXPERIMENT	DAY 1 AM	DAY 1 PM	DAY 2 AM	DAY 2 PM	DAY 3 AM	DAY 3 PM	DAY 4 AM	DAY 4 PM	DAY 5 AM	DAY 5 PM
1	DMU		Tool and Work-Station Check Out	Weaver	Weaver	Staib	Capone	Wright	Crombie		*Hale, Sterger, Chandler, Gullia
1	DIU			Weaver	Weaver	Staib	Capone	Gilstrap	Wright	Crombie	
1	MAT		Tool and Work-Station Check Out								
2	PDU		Tool and Work-Station Check Out	Wickman	Wickman	Capone	Staib	Wright	Gilstrap		Crombie
2	FGE		Tool and Work-Station Check Out	Wickman	Wicckman	Capone	Staib	Wright	Gilstrap		Crombie
3	LARGE SAMS ORU		Tool and Work-Station Check Out	Wickman	Wickman	Capone	Staib	Wright	Gilstrap		Crombie
3	SMALL SAMS		Tool and Work-Station Check Out								
3	HMO/ORS		Tool and Work-Station Check Out								

Table 2-3 DISTRIBUTION RUNS, SAMS TEST #2, WEEK 2

BAY	EXPERIMENT	DAY 1 AM	DAY 1 PM	DAY 2 AM	DAY 2 PM	DAY 3 AM	DAY 3 PM	DAY 4 AM	DAY 4 PM	DAY 5 AM	DAY 5 PM
1	DMU	Weaver	Weaver	Weaver	Weaver			Wolters	Weeks	Carreto	No pm run
1	DIU							Wolters	Weeks	Carreto	No pm run
1	MAT					Weaver	Weaver			Wickman	No pm run
2	PDU							Weeks	Wolters	Carreto	No pm run
2	FGE							Weeks	Wolters	Carreto	No pm run
3	LARGE SAMS ORU	Wickman	Wickman								No pm run
3	SMALL SAMS ORU			Wickman	Wickman			Weeks	Wolters	Carreto	No pm run
3	HMO/ORS					Wong	Jee			Wickman	No pm run

Table 2-4 SAMS DESIGN ORU SIMULATION DATA

ORU SIZE	FOOT RESTRAINT POSITION	INTERFACE POSITION	AVG. TIME	COMMENTS
Large	3" below bolt	side	12s removal	
Large	9" above bolt	saide	9s removal	Overall Optimum Pos.
Large	1'2" above bolt	side	6.5s removal 20.0s insertion	Best visual angle
Large	1'9-1/2" above bolt	side	7.5s removal 22.0s insertion	
Small	3" below bolt	side	4.0s removal 10.0s insertion	Poor visual alignment
Small	9" above bolt	side	3.5s removal 10.5s insertion	
Small	1'2" above bolt	side	3.5s removal 9.0s insertion	Overall Optimum Pos.
Small	1'9-1/2" above belt	side	3.75s removal 10.0s insertion	Poor visual alignment
Small	eyes even with bolt	bottom	7.0s removal 13.0s insertion	Awkward
Small	offset to left, eyes above entire ORU	bottom	5.5s removal 35.0s insertion	Terrible
Small	eyes below bolt	top	6.0s removal 13.5s insertion	

visual cues and the angle at which the subject's arms are used during removal and installation of the ORU. The times given are averages of the several runs at each foot restraint position.

The simulations conducted during the remainder of the week were to those of week one in that each test subject cycled the system and their comments and suggestions were recorded.

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3.0 ROBOTICS SIMULATIONS

3.1 OBJECTIVES

3.1.1 Telerobotics

3.1.2 End Effector

3.1.3 Voice Confirmation

3.2 FACILITY AND TEST HARDWARE

3.2.1 Telerobotics

3.2.2 End Effector

3.2.3 Voice Confirmation

3.3 SIMULATION CHRONOLOGY

3.3.1 Telerobotics

3.3.2 End Effector

3.3.3 Voice Confirmation

(To be supplied)

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4.0 OBSERVATIONS AND CONCLUSIONS

This section includes summary observations on the results of each experiment performed by the Lockheed team in support of the SAMS study contract (neutral buoyancy as well as robotic) and specific conclusions and/or design recommendations resulting from each test.

4.1 NEUTRAL BUOYANCY TESTS

The following are the results of the two neutral buoyancy test series, which included a total of 14 days of dual suit operations in the McDonnell-Douglas UWTF.

4.1.1 Test 1: Orbital Refueling System/Electronic Documentation Experiment

The objective of this experiment was to investigate the feasibility of providing task procedures information to an EVA crewmember, using a Helmet Mounted Display (HMD) driven by an electronic documentation system, and to develop a set of formatting recommendations for the development of future task procedures to be utilized with an HMD. Observations relative to HMD hardware systems were collected secondarily and are presented at the end of this section.

This experiment resulted in a significant industry milestone by accomplishing the first neutral buoyancy evaluation of a Helmet Mounted Display driven by an electronic documentation system. Nine test runs were completed with USAF subjects. The tests clearly indicate the potential that electronic documentation systems have for enhancing EVA crewmember performance, and also provided much insight into how procedures information should be formatted to optimize visability by the crewmember.

Specific recommendations related to the presentation of task information to the EVA crewmember are as follows:

(1) The presentation should be designed to illustrate several related steps of a procedure on verbal command from a crewmember, and then to go automatically into a hold mode, while the crewmember performs those steps. The crewmember should dedicate his attention to the display while it is active, and not begin work until the display goes into the hold mode, to avoid missing details of the presentation.

(2) The task to be performed should be illustrated by clear, high contrast video illustrating the steps to be performed. It is desirable to use high fidelity hardware, with extreme closeups to illustrate details. Care must be taken to indicate to the crewmember the location of the object of the closeup.

(3) The steps to be performed should be described aurally as the video is presented.

(4) At the conclusion of each short series of steps, the display should go into a "freeze frame" mode, illustrating the configuration to be reached at the conclusion of the series of steps. The steps required should be sequentially summarized in cryptic text and display the same frame; the display of the text should not overlay or otherwise occlude the video. The text should include all relevant information on turn counts, direction of rotations, settings, pressures, etc. For example, if the objective of a task is to obtain a specific tool, the freeze frame should show the tool, presented so that all significant features are visible, with the tether configuration(s) clearly shown, and tool setting(s) shown for the upcoming task.

(5) The presentation should be voice-controlled. When a task is completed, the presentation of the next task should be immediately available on verbal command.

(6) The voice control capability should include commands for instantaneous hold, reverse, slow forward, access to detailed "help" instructions, selection of alternate procedures at decision points,

etc.

(7) Caution and warning information relevant to any steps to be performed in a given task sequence should be clearly indicated prior to the crewmember beginning work on that sequence.

(8) A brief statement of the objective of the procedure, the total number of steps in the procedures, and the nominal task performance time should be included at the beginning of the procedure.

(9) The task sequence number (i.e., a sequential number assigned to each successive set of steps grouped for presentation) and the total number of task sequences in the end-to-end procedure, should be displayed at the beginning of each task sequence.

Observations relevant to the design and functioning of the HMD system itself are as follows:

(1) HMD protrusion above and in front of the helmet must be strictly minimized.

(2) The binocular display used for this experiment, (centered, and high in the field of view) was judged comfortable and acceptable by all subjects. The display and any associated shroud must not interface with crewmember vision up and to either side, and should be positioned to permit straight ahead (eyes level) viewing of the worksite in front of the crewmember.

(3) It must be recognized that the use of an HMD in an EVA situation is markedly different from use for a piloting application; accordingly, although several partially silvered mirrors were examined in the initial hardware evaluation runs in the water, to permit a degree of visibility through the display, it was judged more desirable to use a full-silvered, shrouded mirror for this application, for two reasons:

(a) Attention to fine details, maskings, etc. is often crucial to error-free task performance. These details may be masked by the contrasts or action in the field of view beyond the display.

(b) Since the crewmember is not moving or otherwise interacting with the workstation during the presentation of the material on the HMD, it is not important to see what is happening behind the display. The majority of the volume normally visible forward and above the helmet can be monitored by looking around the HMD display, providing that the display is kept reasonably narrow and not allowed to restrict more of the width of the field of view than is occupied by the display itself.

(4) The display screen should be designed to be readily folded or retracted out of the way when not in use, or in the event that the display does occlude vision in a particular situation.

(5) The unit must be designed to withstand minor bumps and impacts without damage or loss of mirror alignment.

(6) The display should not be overly sensitive to head height or lateral position in the helmet.

4.1.2 Test 2: Erectable Structure Lock Assembly Evaluation

This test marked the first neutral buoyancy evaluation of the Able Engineering Company (AEC) erectable lock assembly. The single node work station used in the evaluation is shown in Fig. 4-1. All eight examples of the lock assembly were unfortunately plagued by inadvertant, premature triggering of the preload device during strut installation onto the node. This characteristic, which was not evident in the 1-G checkout runs, limited the ability to get useful installation timeline data, but did not interfere significantly with the evaluation of the flight crew interface aspects of the design. The following observations and design recommendations resulted from the test:

Fig. 4-1 AEC Single Node Workstation

(1) The linear action required to lock the strut onto the node is much less fatiguing than the rotary motion required to lock many current lock assembly concepts.

(2) The lock assembly design required that the strut by fairly precisely aligned prior to insertion into the slot on the node. The crew workload and task performance time could be reduced by modifying the lock assembly to permit 4-5^{o} of strut misalignment.

(3) The lock assembly design required that the strut be rotationally positioned precisely to one of six possible orientations to allow the nex nut on the strut to drop into the slot on the node. This rotational positioning is normally accomplished by a wrist motion, and is somewhat fatiguing and time-consuming. It is desirable that the strut insertion be independent of angular orientation.

(4) The triggering mechanism design should incorporate sufficient friction so that the strut can be handled, with the hand gripping the sleeve which triggers the locking action, without prematurely activating the lock. No separate lock should be required to prevent premature activation.

(5) A technique must be provided to the crewmember to reset a lock if prematurely triggered, or if it becomes necessary to remove and replace a strut.

4.1.3 Test 1: Thermal Blanket Deployment Evaluations

A objective of this test was to determine the feasibility of manual deployment of large thermal blankets (or other soft goods) and manual attachment to a base support structure, by two EVA personnel working without foot restraints (see Fig. 4-2), and to determine the approximate task performance times. The results of this test, as conducted the first time by two Lockheed EVA test crewmembers, are summarized in Table 4.1.

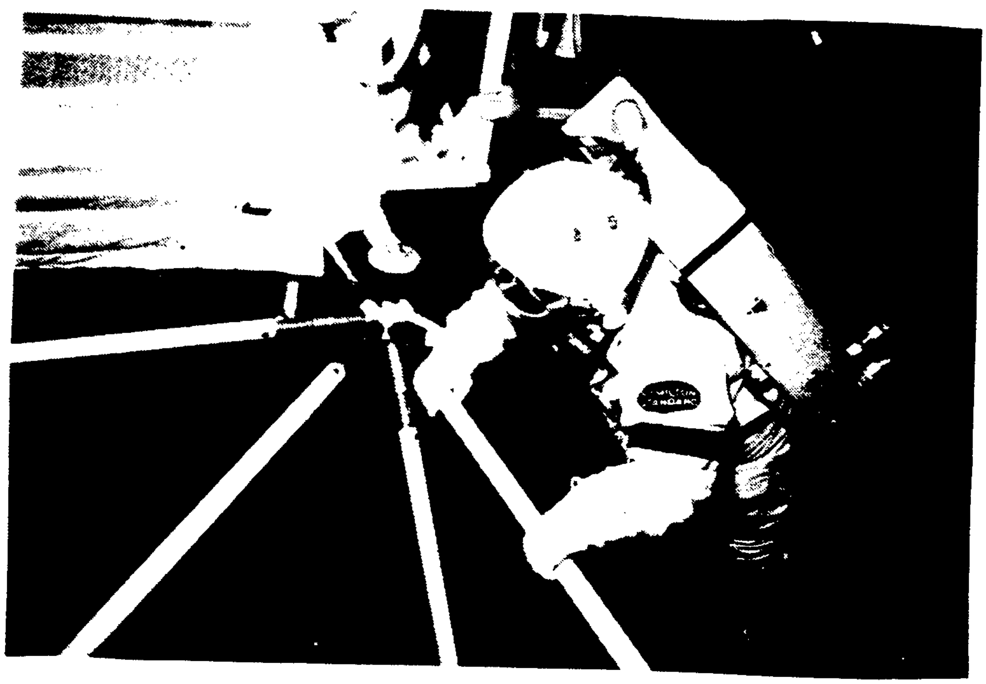


Fig. 4-2 Thermal Blanket Deployment Unrestrained Body Position

TABLE 4-1 THERMAL BLANKET DEPLOYMENT TIMELINE DATA

	TIME (MIN:SEC)
Prepare Dispenser	0:35
Attach Wrist Tethers	0:24
Blanket Reaches First Node	0:39
Blanket Reaches First Node	0:54
Blanket Reaches Third Node	0:58
First 2 Far End Straps Attached and Cinched	0:45
Wrist Tethers Released	0:10
Remaining 3 Far End Straps Attached and Cinched	1:10
Fastex Panel Side Straps Attached and Cinched	
EV-1	(2:30)*
EV-2	0:3:40
Waterbury Clip Panel Side Straps Attached and Cinched	
EV-1	(2:50)*
EV-2	0:4:15
Velcro Strap Panel Side Straps Attached	
EV-1	(3:28)*
EV-2	0:3:40
Third Panel Separated From Dispenser	0:1:10
Third Panel Trailing Edge Attached To Strut	4:22
Total Time To Install 3 Panels	22 min 42 sec

*TIME NOT INCLUDED IN TOTAL
EV-1 AND EV-2 WORKING SIMULTANEOUSLY.
TOTAL TIME IS REPRESENTATIVE OF THE
LONGEST TIME TO COMPLETE TASK.

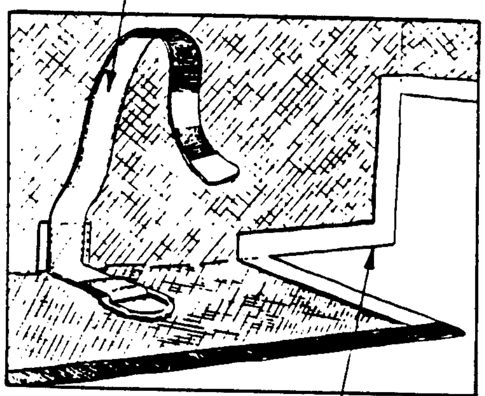
A second objective was to critique the first generation mockup hardware used for this test and formulate a set of design guidelines for use in the Space Based Radar design effort (DRM 4). The following observations and design recommendations resulted from this test:

(1) Manual deployment of large (5 meter wide), flexible panels by two crewmembers working without foot restraints is feasible. Significantly wider panels appear feasible. Three sequentially joined 5 meter long panels were deployed during the test. The results indicate that much longer panels should be deployable under actual EVA conditions. It should be noted, however, that since this concept relies on extensive use of the hands and arms, good hand/glove and glove/strut fit is important.

(2) The roller concept for dispensing the blanket panels is a good blanket management approach.

(3) A slight retraction force incorporated in the dispenser roller appears useful in maintaining blanket position next to the base structure prior to attachment of the deployed blanket. The amount of friction in the dispenser, however, should be kept to minimum. The two test crewmembers estimated that a combined pulling force of at least 40 lbs. was required to deploy the blankets in the test, and it remained fairly constant over the entire deployment cycle. This force resulted from inadvertent contact of the velcro sufaces in the closeout panels along the edge of each blanket panel, and was unacceptably high for sustained deployment operations. It was estimated that a combined force of 1 pound would be a desirable goal.

(4) A spreader bar was incorporated in the leading edge of the first panel to maintain a streamlined shape in the water. This may also be necessary in the vacuum environment so that the leading edge shape can be maintained without requiring the crewmember to maintain tension across the leading edge. (Tension applied in this way would



(Other Concepts To Be Supplied)

Fig. 4-3 Blanket To Strut Fastener Concepts tend to cause crewmember rotation around the strut, which would have to be resisted by the hand grip on the strut.)

(5) All three blanket-to-strut fastener concepts evaluated were operable, however, the Fastex concept was much preferred over the modified Waterbury clip or the Velcro strap. The three concepts are illustrated in Fig. 4-3.

(6) No significant problems were encountered in separating the deployed panel(s) from the succeeding panel still in the dispenser (Fig. 4-4). The Velcro panel-to-panel attachment concept was the sole concept evaluated, however it appeared that the Fastex concept also would have been satisfactory. It is perferable to have a concept which releases easily with one hand, while the other hand is used to grip the strut adjacent to the separation interface, to maintain body position. The two crewmembers started at the two corners of the panel and worked their way to the middle.

(7) Panel-to-panel closeouts around a 90^{o} corner were also evaluated and found to be feasible, again working without foot restraints. The two crewmembers started at mid-panel, working together to stretch one closeout panel around the strut, and then pull the second closeout panel across the first, and attch it to the first with Velcro. Three observations were:

(a) It would be desirable to develop a panel design concept which does not require separate closeout panels.

(b) If closeout panels are employed, a stowage concept should be devised to keep the panels folded back and lightly secured to the panel during panel deployment, so that they remain out of the way during panel attachment to the struts.

(c) Some type of mobility loops are needed which are accessible to the crewmember after panel closeouts are installed to permit translation along the outside of a structure covered with

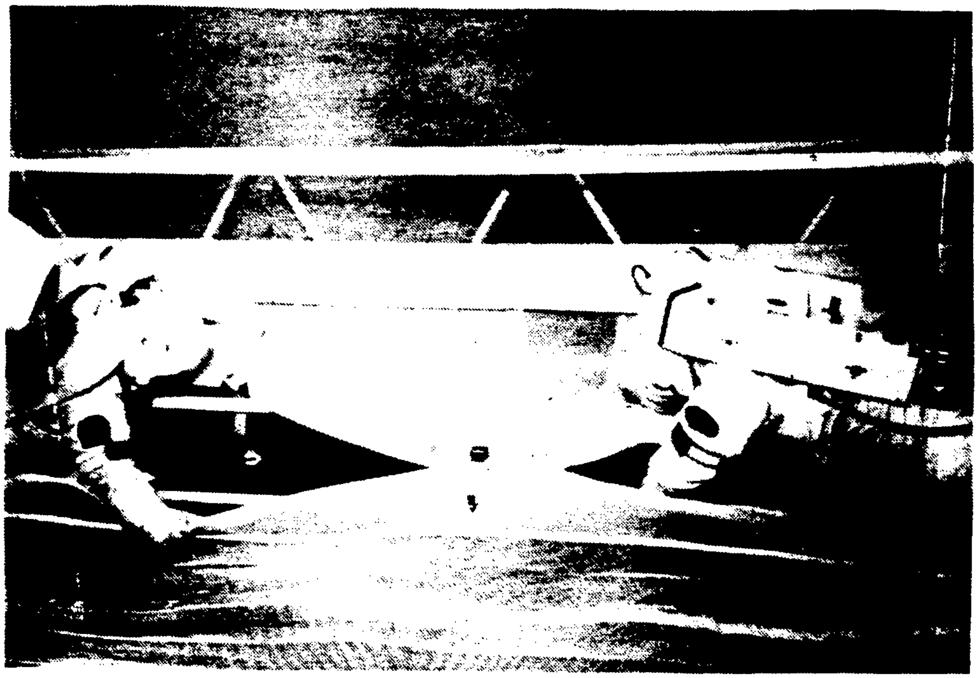


Fig. 4-4 Separating The Deployed Thermal Blankets

panels. The loops should be co-located with the straps which attach the panels to the truss structure to give a degree of rigidity to the loops.

4.1.4 Test 1: Environmental Enclosure Evaluation

Two predeployment packaging concepts are possible for the environmental enclosure - folded, and rolled. The folded approach was used for this test.

It was apparent during the pretest SCUBA checkout of this hardware that deployment in the EMU's would be unnecessarily tiring and time consuming, without additional straps and fasteners aid in regulation deployment. Therefore, suited activities in support of the environmental enclosure were limited to evaluation of the deployment winch operations (Fig. 4-5), operation of the structural attachment concepts (a strap and Fastex fastener concept), operation of the crew entry door (opening, closing, and locking), crew entry and exit through the crew entry door (Fig. 4-6), and crew mobility inside the deployed enclosure. No major problems were encountered. It was noted that a bi-fold entry and exit door would have been easier for a single EVA crewmember to operate than the large (54" square) single fold door evaluated during this test.

Subsequent to the test, concepts for suited deployment of a 5 m cubical baggie have been developed for both the rolled and the folded launch configurations. It is believed that the rolled approach is easier and could be accomplished with the hardware as tested. (See Fig. 4-7). The folded approach also appears feasible, however, it requires the addition of more straps and fasteners to permit the crewmember to divide the enclosure deployment into phases, so each newly deployed portion can be fastened to the truss structure before the next portion is released. The phased approach to enclosure deployment from the folded configuration is illustrated in Fig. 4-8.

4.1.5 Test 2: EVA Tool Requirements Development

The emphasis of the second neutral buoyancy test series was to develop functional requirements for EVA hand tools to support electrical and

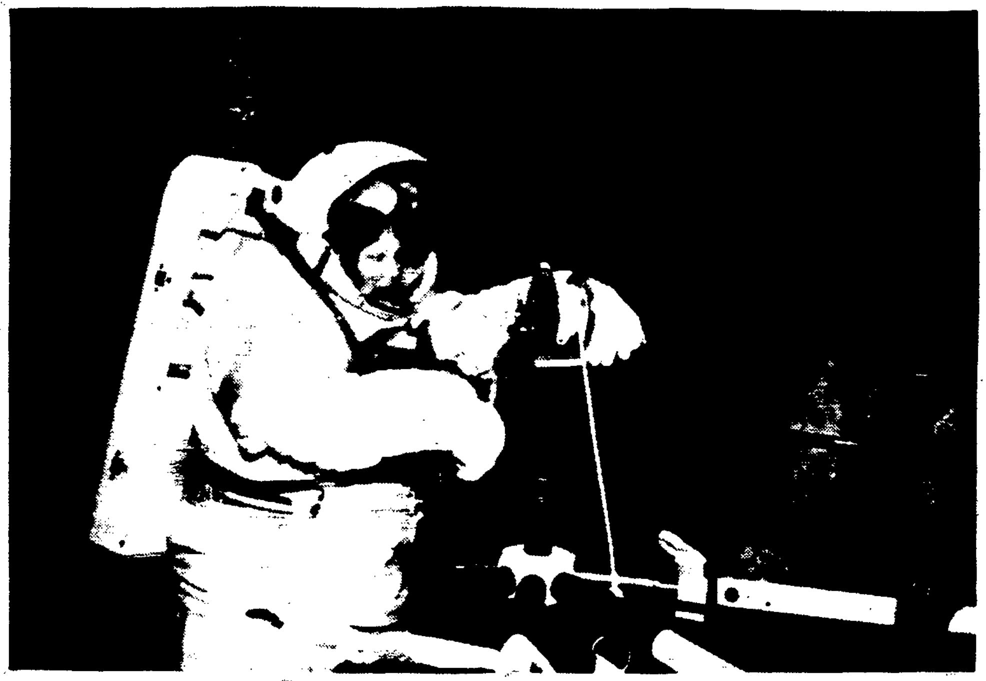


Fig. 4-5 Environmental Enclosure Deployment - Winch Evaluation

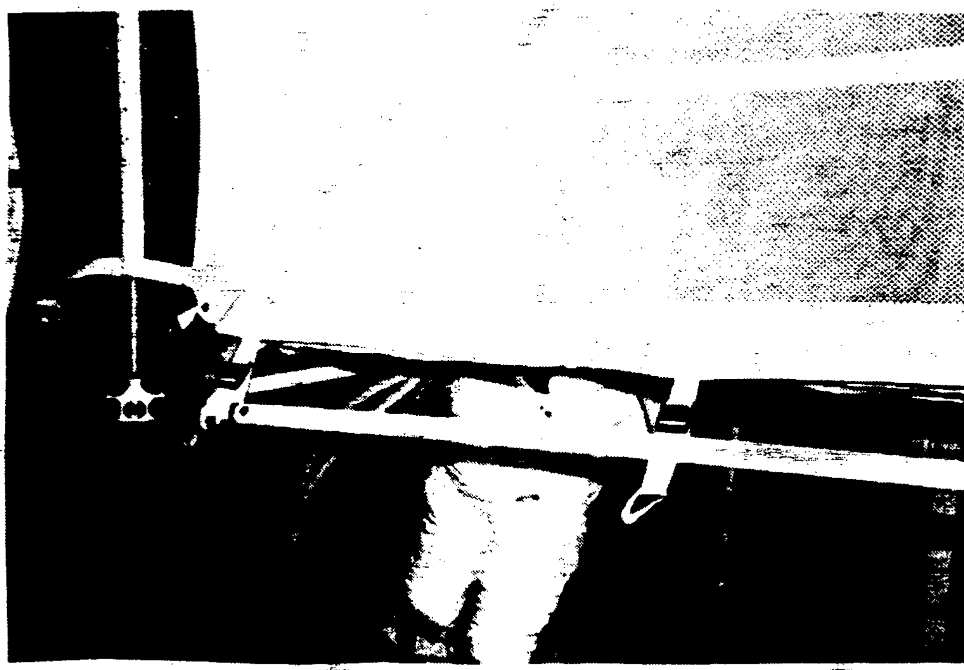


Fig. 4-6 Entry Into The Environmental Enclosure

(To Be Supplied)

Fig. 4-7 Environmental Enclosure Deployment From Rolled Storage Configuration

(To Be Supplied)

Fig. 4-8 Environmental Enclosure Deployment From Folded Configuration

(To Be Supplied)

Fig. 4-9 Data Management Unit

mechanical connector mate/demate operations. As part of this objective, the most complex ORU exchange task utilizing the Data Management Unit as the ORU, Fig. 4-9, was performed end-to-end by the senior Lockheed EVA test crewmember. The purpose of this test was to obtain a total remove/reinstall timeline for a complex current technology spacecraft equipment item, identifying the distribution of time between the various components of the task, and identifying task elements leading to excessive fatigure. Special emphasis was placed on identifying fatigue-inducing aspects of tool design. The results of this test are summarized in Table 4-2. A detailed breakdown of the removal data is presented in Table 4-3, and a detailed breakdown of the reinstallation data is presented in Table 4-4.

It should be emphasized that the individual removal and reinstallation times are actual working times, beginning with the appropriate tool or connector pigtail in hand, and the task elements visually located. Extreme care was taken to avoid bending pins or stressing wires through inadvertent contact with tools or hands; no mockup damage was sustained during this test.

Hand and finger fatigue was a significant factor in this test, even though the actual working time was distributed over three separate dives on two successive days. Test crewmember comments indicated that, given the test configuration and tools as evaluated for this test, the measured task performance times should be doubled to allow a minimum acceptable degree of hand and finger recovery between tasks. In addition, development of a projected orbital timeline for this task would need to include time to prepare the worksite (open the access door, install door stay, install and position the foot restraint, adjust the foot restraint periodically during the task, set up and restore tools, etc., and then reverse these steps to close out the task). In summary, it appears that this task, if performed end-to-end on-orbit, would require 6 - 7 hours of EVA time.

Specific observations and recommendations from this test which relate to selected tools from the recommended generic tool set for early SAMS missions are the following:

TABLE 4-2 DMU REMOVAL/REINSTALLATION TIMELINE SUMMARY

	ITEM COUNT	TIME (MIN:SEC)
Connector Removal		
Forward Cannon	(12)	2:05
Forward Coax	(7)	8:01
Aft Cannon	(12)	2:24
Aft Coax	(7)	13:15
Bolt Removal (20 bolts)		15:06
ORU Removal		:30
ORU Repositioning (includes alignment guide installation)		:45
Bolt Installation	(20)	38:09
Connector Reinstallation		
Forward Coax	(7)	16:00
Forward Cannon	(12)	16:05
Aft Coax	(7)	13:10
Aft Cannon	(12)	34:41
Total Working Time:		160 min 11 sec

NOTE: Total working time is on-station time spent actually installing or removing bolts or connectors. Workstation preparation, foot restraint ingress/egress, tool set up, tool retrieval for each task, rest periods, workstation closeout not included.

TABLE 4-3 DMU CONNECTOR REMOVAL TIMELINE DATA

CONNECTOR #	CONNECTOR TYPE	TOOL USAGE HAND	0^{o} PLIERS	LEASAT	TIME MIN:SEC	NOTES
J20	Cannon		x		:19	
J12	"		x		:14	
J14	"		x		:13	
J3	"		x		:14	
J8	"		x		:14	
J6	"		x		:11	
J4	"		x		:12	
J24	"		x		:10	
J10	"		x		:10	
J13	"		x			Conn. missing
J7	"		x		:16	
J2	"		x		:11	
J26	Coax	x	x		1:48	
J30	"	x	x		1:12	
J28	"		x		2:17	
J32	"		x		1:21	
J34	"		x		2:50	
J36	"					Conn. missing
J38	"					Conn. missing
J5	Cannon		x		:12	
J1	"		x		:11	
J16	"		x		:07	
J18	"		x		:12	
J13	"		x		:08	
J11	"		x		:09	
J15	"		x		:06	
J9	"		x		:08	
J22	"		x		:10	
J19	"			x	:12	
J21	"			x	:07	
J23	"			x	:23	
J25	Coax	x	x		1:00	
J27	"	x	x		:58	
J29	"		x		:56	
J31	"					Conn. missing
J33	"		x		2:02	
J35	"		x		1:43	
J37	"		x		1:22	

TABLE 4-4 DMU CONNECTOR REINSTALLATION TIMELINE DATA

CONNECTOR #	CONNECTOR TYPE	TOOL USAGE HAND	0° PLIERS	LEASAT	TIME MIN:SEC	NOTES
J38	Coax					Conn. missing
J36	"					Conn. missing
J34	"	x	x		1:36	
J32	"	x	x		1:48	
J30	"	x	x		2:07	
J28	"	x	x		1:07	
J26	"	x	x		1:53	
J2	Cannon		x		:41	
J4	"		x	x	10:21	
J6	"			x	1:00	
J8	"			x	4:36	
J3	"			x	9:10	
J7	"			x	:32	
J14	"			x	:59	
J12	"			x	1:08	
J10	"			x	:50	
J20	"			x	2:20	
J24	"	x		x	:11	
J17	"	x				Conn. missing
J37	Coax	x			2:25	
J35	"	x			2:09	
J33	"	x			3:39	
J31	"	x				Conn. missing
J29	"	x			1:21	
J27	"	x			2:34	
J25	"	x			1:39	
J5	Cannon			x	5:22	
J19	"					Data missing
J21	"					Data missing
J1	"	x			:14	
J16	"	x	x		1:59	
J18	"	x	x		:35	
J13	"	x	x		:55	
J11	"		x		1:04	
J15	"		x		:46	
J9	"		x		:19	
J22	"			x	1:05	
J23	"					Data missing

4.1.5.1 In-line Connector Pliers. This type of tool is necessary to install and remove closely spaced cannon-type electrical connectors (when spacing precludes gloved-hand access), when the access envelope is in line with the connector long axis. In cases where gloved hand access is marginal, use of a tool of this type will reduce the potential for inadvertant damage to adjacent wires, and will also eliminate the potential for damage to the glove from exposed thread sections on adjacent "open" connectors.

Two separate tools were evaluated for this application - the HST Zero-Degree Connector Pliers (Fig. 4-10) and the LEASAT vise grips (Fig. 4-11). Functionally, the major diffrence was that the zero-degree pliers required constant hand pressure to maintain the grip on the connector, while the vise grips could be locked on the connector. There were desirable and undesirable features of each tool, however, the LEASAT pliers required less energy to use, and provided more tactile feedback to the operator, because the hands were relaxed during most phases of connector positioning and engagement. The major drawback to the LEASAT pliers for this application was that the tool does not indicate correct settings for specific connector sizes, so it was easy to clamp too tightly on a connector ring and permanently deform the ring. Several connector rings on the mockup were deformed during the test series to a degree that significantly interfered with connector reattachment.

Specific recommendations for the SAMS In-line Connector Connector Pliers are:

(1) Jaws should be positioned so that, when the pliers is closed on a connector, the connector is held with its long axis parallel, and as nearly as possible, coincident with the long axis of the body of the tool. The two objectives of this feature are first, to permit use of the tool long axis as the primary alignment aid when reinstallating connectors, and second, to allow the end of the tool long axis opposite the connector to rotate in one spot during connector mate/demate, rather than describing a circle.

(2) A "T-bar" handle, as incorporated on the LEASAT tool, should be included, but rotated 90^{o} from the plane of travel of the vise grip

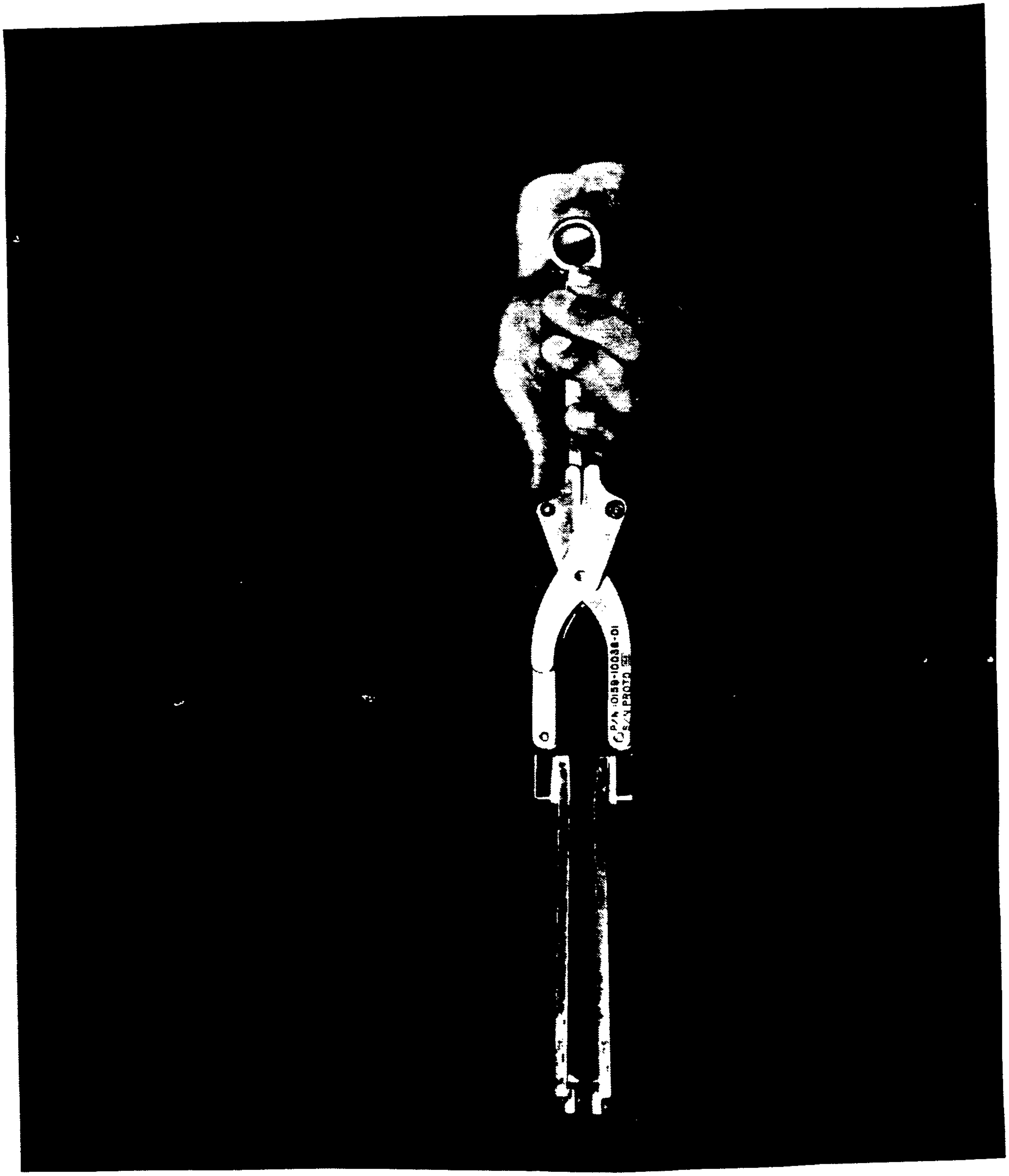


Fig. 4-10 HST-Zero Degree Connector Pliers

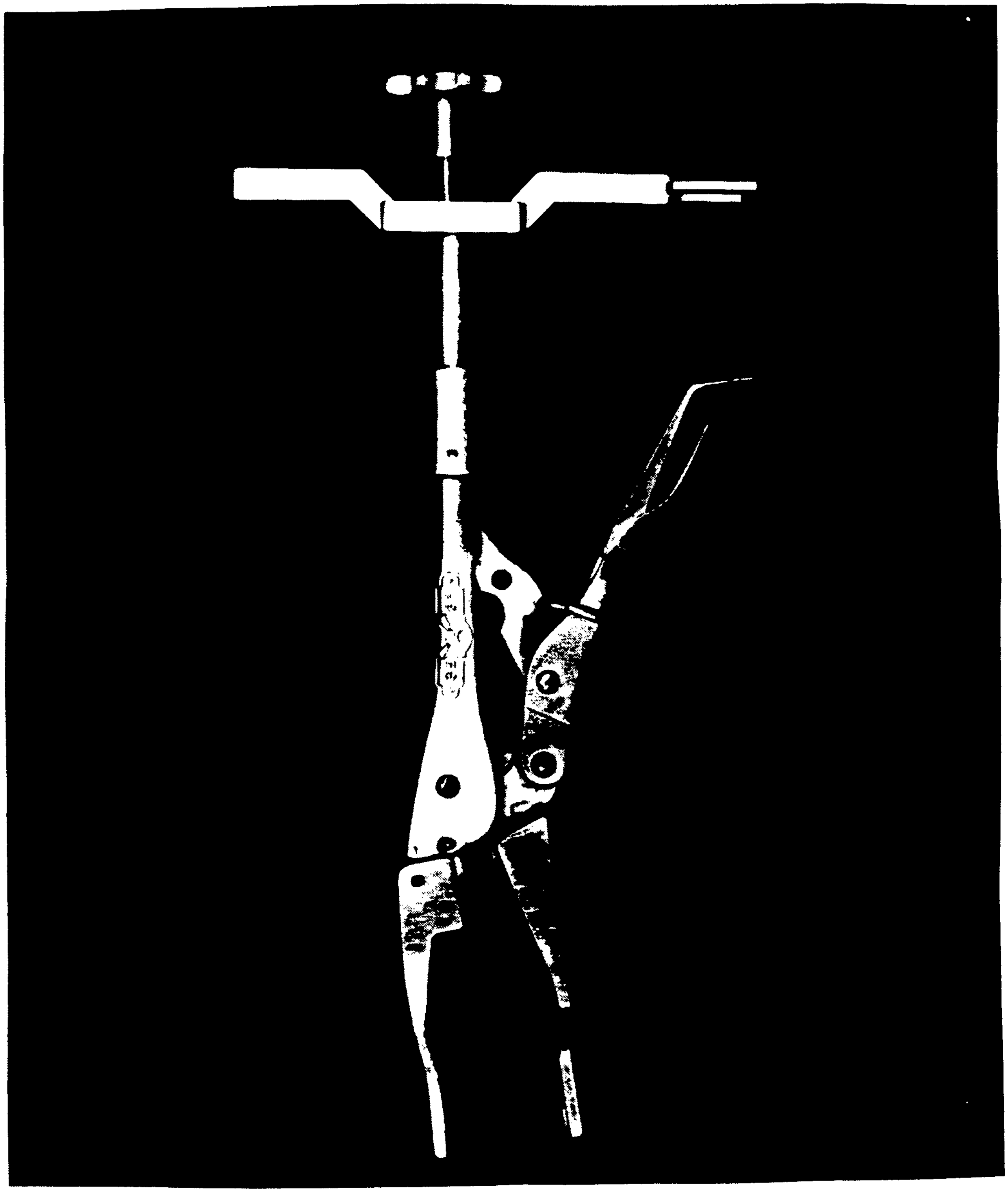


Fig. 4-11 LEASAT Vise Grip Connector Tool

(To Be Supplied)

Fig. 4-12 Recommended Cannon Connector Tool Jaw Configuration handle, to provide a clear access path to the vise grip handle.

(3) The tool jaws should be designed to permit visibility of the connector ring during as much of the mate/demate rotational cycle as possible, to permit verification of non-slippage. This recommendation is illustrated conceptually by Fig. 4-12.

(4) The tool should incorporate spring-loaded shoulders to aid in properly positioning the jaws on the connector ring. The shoulders incorporated in both the HST zero degree and the 90^{o} connector pliers (see Fig. 4-13) worked very well for this function.

(5) The tool should incorporate a feature to allow presetting of the jaws to the specific connector size prior to gripping the connector ring. A vernier feature with substantial built-in friction should be incorporated to permit adjusting the preset position if required to accommodate tool wear and tolerance buildup.

(6) The tool should incorporate 2 jaw settings for each connector size - a "soft" grip setting which allows the crewmember to hold the tool with one hand while inserting the pigtail half of the connector into the jaws, and a "hard" grip setting which grips the ring securely for the mate/demate rotation. The soft position should be maintained by detent only - not a separate mechanical stop which must be released to go to the hard grip position. The soft versus hard positions should be readily identifiable visually.

(7) The tether ring should be designed to rotate around the tool shaft to eliminate tether "wind-up". The ring should only have one degree of freedom (rotation about tool long axis) to facilitate tether attachment.

4.1.5.2 <u>90^{o} Connector Pliers:</u> The function of this tool is to install and remove closely spaced cannon-type electrical connectors (where spacing and/or access limitations preclude gloved hand access), when the access is

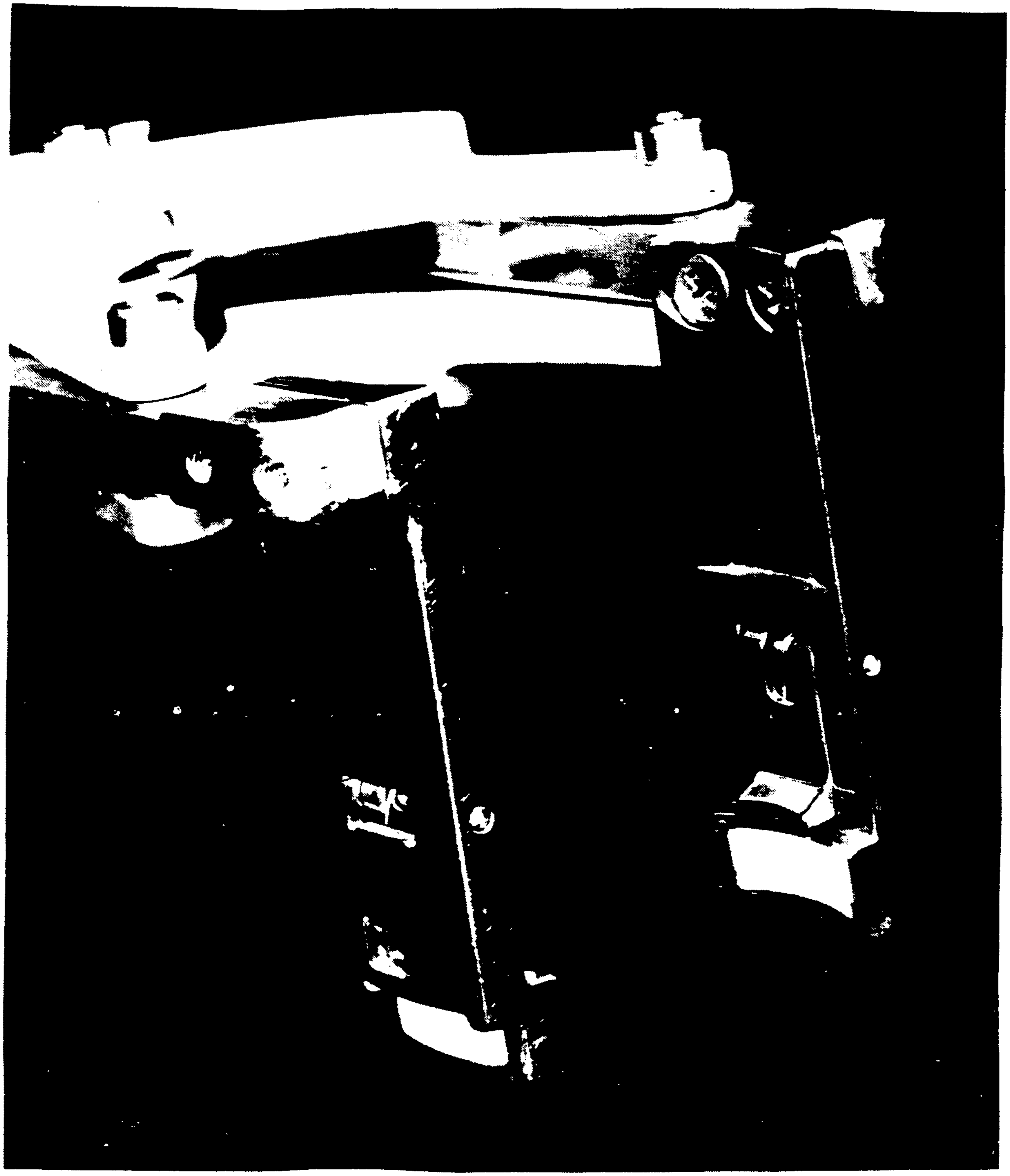


Fig. 4-13 Spring Loaded Shoulders in the Jaws of the 90^0 Connector Pliers

Fig. 4-14 HST 90° Connector Pliers

perpendicular to the connector long axis.

The HST 90° Connector Pliers, (Fig. 4-14) was evaluated for this application. The tool was otherwise similar in design to the HST Zero Degree Connector Pliers; comments 3, 4, 5, and 6 from the previous section (Zero Degree Connector Pliers) also apply to the 90° Pliers.

4.1.5.3 Zero Degree Coax Connector Pliers. The purpose of this type of tool is to remove and reinstall small, single wire coax connectors requiring multiple turns. No tools of this type were available for evaluation during the CSTS test; the small connectors were removed and replaced largely by hand. Manual operations resulted in a high degree of fatigue, significant glove wear, a tendency to "wind-up" the connector wire, and significant risk of glove-induced damage to adjacent single wire connectors. Observations and suggestions made during the test resulted in the development of the following recommendations of design requirements for a zero-degree coax connector pliers.

(1) The tool should incorporate a locking feature to maintain the grip on the connector.

(2) The locking feature should include a "soft" grip position to permit inserting the pigtail half of the connector in the jaws with one hand while holding the tool in the other hand, and a "hard" grip position for use in turning the connector.

(3) The tool should be capable of multiple 360° turns of the connector, without removal from the connector, and without wrapping the connector wire.

(4) The palm wheel used in the ESSEX wrench (Fig. 4.15) should be considered for this tool to provide a crew interface which permits multiple turn inputs with minimal wrist/hand/finger energy expenditure.

4.1.5.4 Coax Connector Hex Head Tool. The objective of this tool is to

Fig. 4-15 Essex EVA Ratchet Wrench

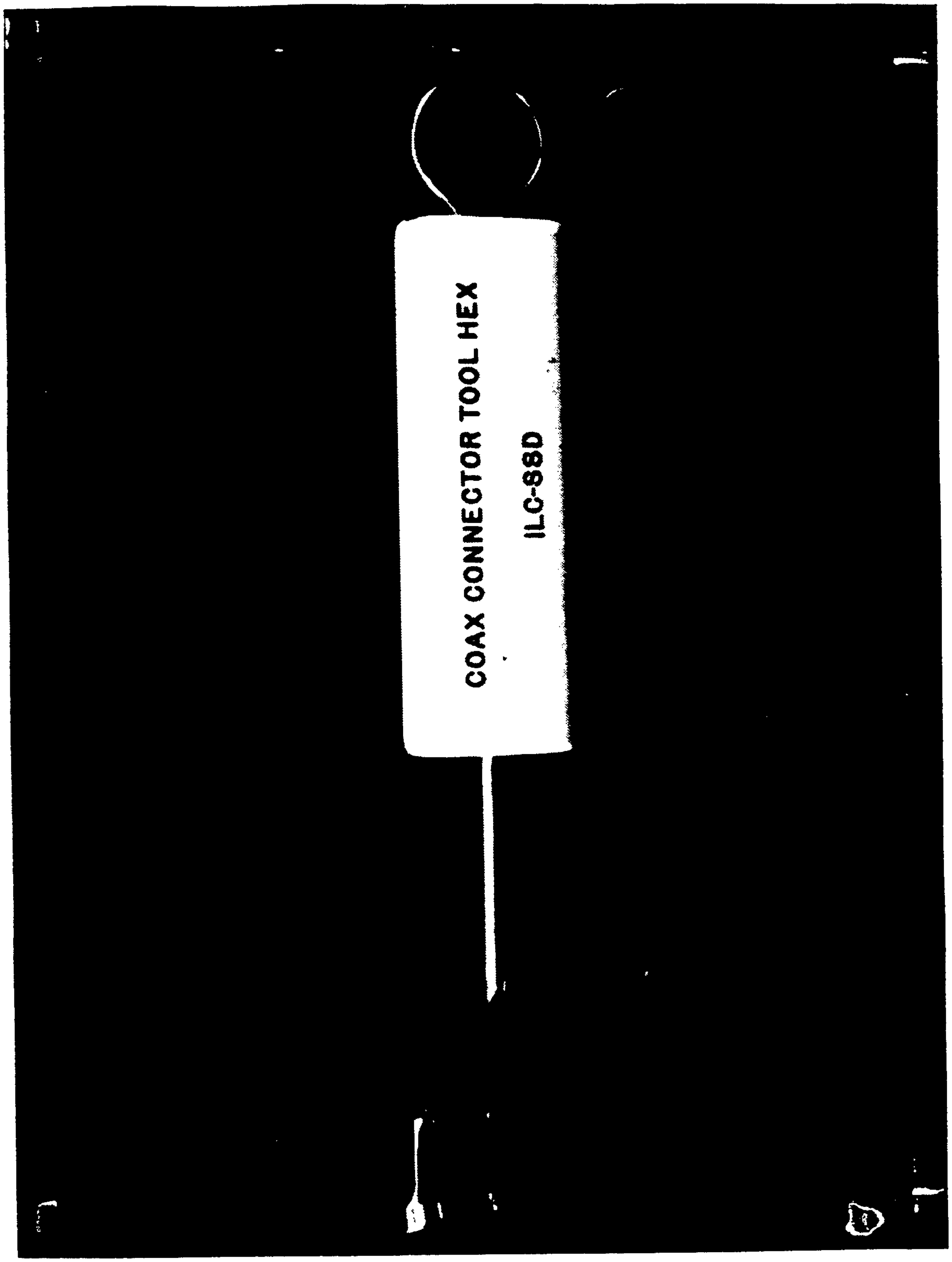


Fig. 4-16 Coax Connector Hex Head Tool

Fig. 4-17 Coax Connector Hex Head Tool

release/tighten hex-headed fasteners and/or connectors. The tool evaluated was a simple offset open end wrench with EVA handle and tether ring (Fig. 4-16). Details of the wrench end are shown in Fig. 4-17. The tool was used to mate and demate very closely spaced coax connectors with hex heads. The tool performed well as designed; the only significant improvement suggested was the following:

(1) Addition of a shoulder to the tool head would allow installation of connectors with the tool, using only one hand. (As evaluated, the tool requires that the crewmember position the connector with one hand while tightening with the wrench in the other hand.). Consideration should be given to locating the shoulder at the mid-height position in the head of the wrench, so that the wrench can be used to hold a connector in either direction - this feature would require increasing the thickness of the head.

4.1.5.5 D Connector Mate and Demate Tools. The objective of these tools was to aid the removal or replacement of closely-spaced D connectors. The mate tool evaluated during the CSTS tests is shown on the left in Fig. 4-18; the demate tool evaluated is shown on the right. Both tools included width adjust capability (one jaw fixed; the other adjustable between positions 1 and 5, with detents at each numbered position). Both jaws on each tool were designed to rotate the full 360° about the attach point to the handle, with detents in each 90° pisition.

The demate tool worked well as designed. The mate tool, however, proved difficult to use, largely due to the fact that the tool could not grip the connector tightly enough to counter the loads imposed by the wiring harness. As a result of the CSTS evaluation, the following design recommendations were developed for a generic D connector mate tool for SAMSS missions:

(1) The requirement for including jaw rotation capability should be carefully reassessed, and dropped if possible. If the capability can be justified, it should be designed to require a deliberate, significant effort, to preclude inadvertent rotation and release of

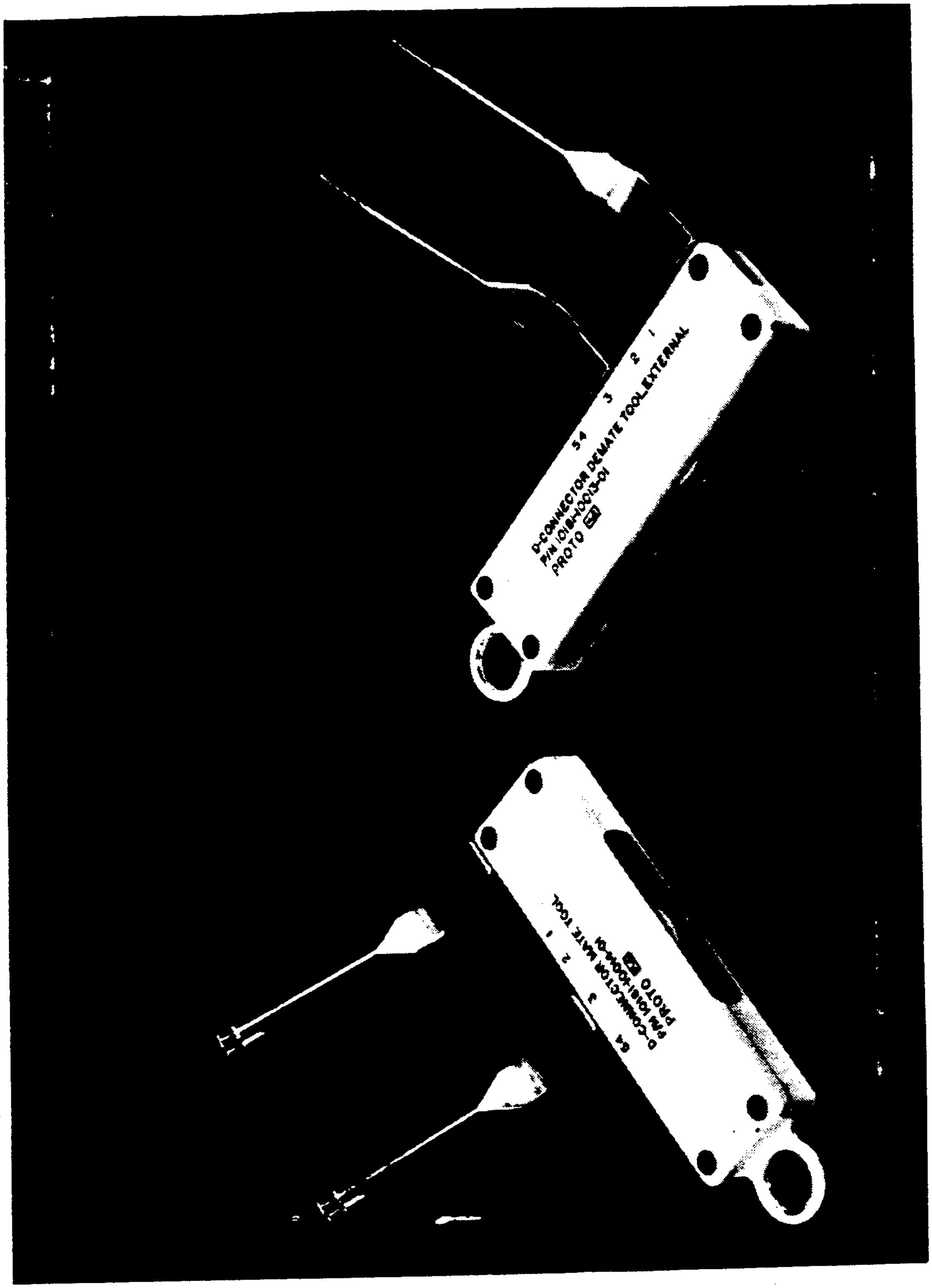


Fig. 4-18 "D" Connector Mate and Demate Tools the connector during installation.

(2) The jaw spacing should be undersized so that, when the jaws are set for a specific connector, the jaws must be forced apart at the connector end to allow the connector to be inserted.

4.1.5.6 Screwdriver. The purpose of the screwdriver was to release and resecure small captive screws. The screwdriver evaluated during the tests was a blade type, in the form of an extension designed for use with the ESSEX EVA ratchet wrench. A set of extensions designed for use with the ESSEX wrench are shown in Fig. 4-19; the blade screwdriver is shown on the right. A Torque Tip Drive extension is shown on the left. The ESSEX wrench itself is shown with a socket extension in Fig. 4-15.

The screwdriver tip was surrounded by a circular shroud to aid the EVA crewmember in maintaining position on the screwhead. A small coiled spring section was included just behind the head of the screwdriver to permit off-axis access to screws. These features are shown in the closeup of the blade tip (Fig. 4-20).

4.1.5.7 EVA Ratchet Wrench. The EVA ratchet wrench developed by ESSEX is a manual ratchet modified to enhance utilization in the pressure suit, the principal modifications are the addition of a palm wheel and an enlarged, more accessible direction reversing lever. The wrench works well for its intended purpose, however, the following suggestion would reduce hand fatigue in extended operation:

(1) Modify palm wheel to include a thumb ring instead of the center mounted button, to permit operation with thumb and fingers positioned as shown in Fig. 4-21, as opposed to Fig. 4-22. The extension release function represented by the center-mounted button would be incorporated in the thumb ring, or eliminated entirely if the McTether system is used. The thumb ring would be designed with a profile low enough to not impede gripping the palm wheel.

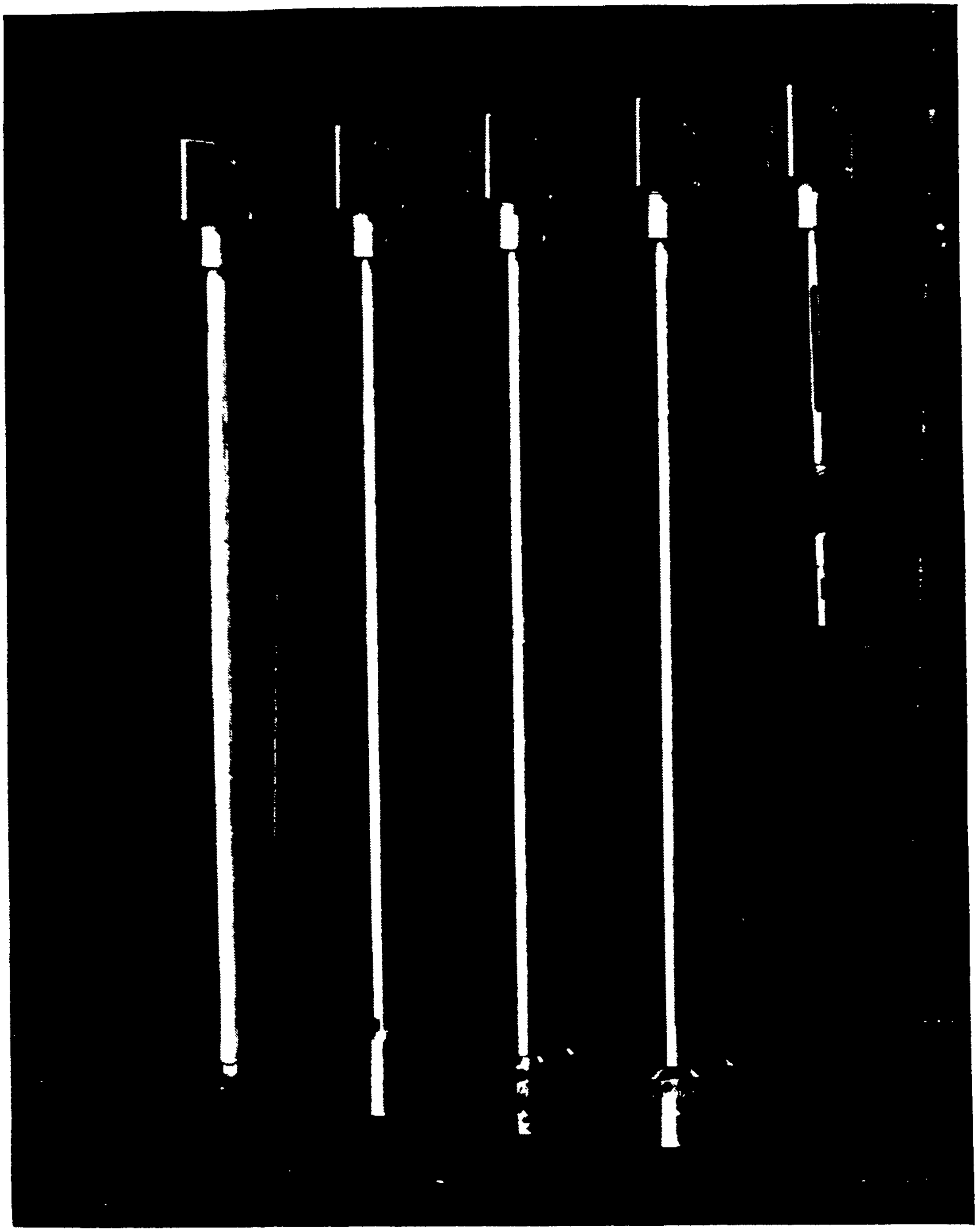


Fig. 4-19 Extensions for the Essex EVA Ratchet Wrench

Fig. 4-20 Shrouded Screw Driver Blade Tip

Fig. 4-21 Relaxed Finger Position for Gripping the Palm Wheel

Fig. 4-22 Palming the Essex Ratchet Wrench

4.1.6 Test 2: SAMS Designed ORU Conclusions/Recommendations

4.1.6.1 Alignment Aids Large ORU.

The optimum position for the installation and removal of the large ORU placed the test subjects eyes 9" above the attach bolt of the "sword and scabbard" system. The test subject could observe, from this position, the insertion of the blade into the receiving rail. Therefore, initial visual alignment was not overly difficult. However, test subjects showed some difficulty with the insertion of the ORU once initial alignment had been completed. The ORU tended to rotate in three axis about the point of contact between the sword and scabbard. Much of this can be taken care of with improved interface design, but some type of physical alignment aid would be helpful. The fact that the receptical bay was at an angle away from the crewmember seemed to cause consistent problems. The test subjects attempted to insert the ORU straight into the bay, not taking into account that the base structure is circular and curves away from them. A physical alignment aid on the side of the ORU opposite the interface system would help solve this problem.

4.1.6.2 Alignment Aids - Small ORU.

With the interface system installed on the side of the receptical bay, the system alignment was much the same as the large ORU except the motions were less exagerated due to the smaller physical size of the box. Alignment with the interface system at the bottom of the bay proved to be very difficult as this operation (from the higher of the two PFR positions) was completely blind. Attempts were made using the side of the scabbard, the overall ORU shape relative to the bay and the back of the ORU relative to the bay as alignment aids, but to no avail. With the PFR positioned directly below the bay, alignment was easy, as the test subject could sight directly down the interface system, but the physical handling of the box was difficult due to the face it was directly overhead.

Alignment with the top mounted interface system was not quite as difficult, because the test subject was eye level with the interface system and could see the initial alignment.

4.1.6.3 Interface Design.

During the actual physical operation of the "sword and scabbard" system difficulties were encountered due to damage to the Delron channels of the scabbard caused by the sword. Also the relatively small contact area of the interface system allowed too much movement of the box about this one attach point. To solve these problems, the system should be designed with a broader base with a much more shallow angle for alignment to avoid the sword catching the scabbard and causing damage. In order to aid with the alignment problem mentioned earlier, the redesigned system also allows for angular misalignment about a vertical axis through the attach point.

4.1.6.4 Crew Aids.

Crew aids are required on both the spacecraft and the ORU itself. During tests conducted with the interface system side mounted in the bay, test subjects used the door knob on the adjacent bay door as a handhold during the insertion and retraction of the ORU. This should be replaced by a handrail on the structure between the bays. During the top and bottom mounted runs, the sides of the bay and the adjacent handrails were used. Still, an optimized handrail system could be an improvement.

The handholds on the ORU itself should be placed as close to the center line of the interface system as possible. A handhold on the connector interface plate of the ORU itself is a possibility.

The flush mounted handholds proved useful only during the tests of the bottom mounted interface when the test subject was in a position that proved to be relatively useless for alignment. It is therefore recommended that these handles be withdrawn from consideration as they are very costly in terms of internal volume of the ORU.

4.1.6.5 Crewmember Positioning.

Proper positioning of the EVA crewmember for the SAMSS designed ORU tasks is a tradeoff between visual alignment and physical handling of the ORU. The optimum position for the operation of the large ORU was with the foot restraint offset to the left of the bay and the crewmembers' eyes 9" above the interface bolt. Handling was actually easier from the next higher position, but the subjects arms interfered with the visual alingment of the system. The optimum position for the small ORU was found to be 5 inches higher for handling reasons. Difficulties with handling occurred with the top and bottom mounted interfaces because the ORU was in awkward position, such as overhead. In general, the EVA crewmember should be positioned so the arms can operate directly in front of the chest area while making sure the system can be visually aligned.

A general observation relative to tests such as the two reported herein is that effective, efficient testing involving the amount of hardware normally used in full scale neutral buoyancy tests requires the on-site ability to respond quickly to numerous needs to modify, reconfigure, repair, or fabricate equipment items. Although the capability to readily respond to these requirements exists at MDAC, this need was not adequately provided for by the current contractual arrangements.

4.2 ROBOTICS TESTS

(To Be Supplied)

APPENDIX A ORS PROCEDURES

This section includes the STS-41G Orbital Refueling System (ORS) hydraulic transfer experiment procedures as adapted by LMSC for the Helmet Mounted Display/Electronic Documentation Experiment.

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LMSC SAMS ORS PROCEDURE TAPE (JAN. 1987)

STEP NO.	TASK
1.	Grasp hand knob.
2.	Fold back thermal covers.
3.	Egress foot restraint.
4.	Unlatch and stow landing brace.
5.	Remove tool cover.
6.	Stow tool cover.
7.	Ingress foot restraint.
8.	Locate seal verification tool on map.
9.	Tether seal verification tool - left ORS tether ring.
10.	Check pressure on gauge.
11.	Restow and untether seal verification tool.
12.	Locate wire clippers on tool map.
13.	Tether wire clippers to wrist tether ring.
14.	Clip and bend away safety wires on dust cover.
15.	Restow and untether wire clippers.
16.	Locate dust cap removal tool on map.
17.	Wrist tether dust cap removal tool.
18.	Remove dust cap with 6-3/4 turns CCW.
19.	Restow and untether dust cap removal tool.
20.	Locate ball valve on tool map.
21.	Tether both ball valve caps to right ORS tether ring.
22.	Unstow ball valve and remove small cap.
23.	Install ball valve on uncovered port - ST/CW - making sure safety catch engages.
24.	Close ball valve. Raise gold handle.
25.	Remove silver cap from end of ball valve.
26.	Tether seal verification tool (verbal instructions on which tethers to use).
27.	Remove red cap. Put tethered cap to left of tool tray.

LMSC SAMS ORS PROCEDURE TAPE (JAN. 1987)

28. Install tool on ball valve - 6T CW until tight.

29. Release safety.

30. Turn green knob CCW as far as possible.

31. Check pressure gauge.

32. Open ball valve.
Pull gold handle down.

33. Check pressure gauge.

34. Close ball valve.
Raise gold handle.

35. Turn green knob CW to original position.

36. Reengage safety.
Turn bolt CW/90°.

37. Remove seal verif. tool - 6T CCW.

38. Replace end cap.
Restow and untether.

39. Lower then raise gold handle on ball valve.

40. Locate nut retainer tool on tool map.

41. Tether nut retainer tool to wrist tether ring.

42. Unstow and tether end cap to left ORS tether ring.

43. Remove protective cap.

44. Slide red collar away from knob.

45. Thread red collar onto ball valve - 4-1/2 T CW.

46. Open ball valve.
Pull gold handle down.

47. Insert tool shaft thru ball valve.

48. Make 6T CCW and retract tool shaft. Important to count turns here.

49. Close ball valve.
Raise gold handle.

50. Remove tool 4-1/2 T CCW on red collar.

51. Check tool end for nut and cap
- with nut and cap.
- without nut and cap.

LMSC SAMS ORS PROCEDURE TAPE (JAN. 1987)

52. Replace tool cap.
53. Untether cap.
54. Restow and untether tool from wrist tether ring.
55. Locate multipurpose tool on tool map.
56. Tether multipurpose tool cap to left ORS tether ring.
57. Remove tool cap.
58. Slide large blue collar away from tool's hose.
59. Thread collar onto ball valve 4-1/2 T CW or until tight.
60. Open ball valve.
    Pull gold handle down.
61. Insert tool shaft thru ball valve until contact is made/felt.
62. Rotate knurled handle 3-1/2 T CW or until tight.
63. Push knurled handle to engage red tabs over tool lip.

"Procedure Complete"

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APPENDIX B Helmet Mounted Display Test Data

This section includes the data from each HMD test run during the first neutral buoyancy test series.

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TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
1. GRASP HAND KNOB					
2. FOLD BACK THERMAL COVERS	1	73	Trouble finding Velcro tabs	Hold tape for a second OK go ahead	
	2	107			
	3	56		Audio on ORS tape fine	
	4	29			
	5	13	Landing brace was stowed before covers were finished		
	6	46			
	7	46			
	8	103			
	9	35			
	10				
3. EGRESS FOOT	1			Ignored, still in PFR	
	2			NA	
	3			Ignored, still in PFR	
	4			NA	
	6			NA	
	7	23			
	8			NA	
	9			Ignored, still in PFR	
	10			NA	
4. UNLATCH AND STOW LANDING BRACE	1	21			Leslie offered to pause tape, declined
	2	33			
	3	17			
	4	12			
	5			Task completed during previous task	

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
4. (Cont'd)	6	45			
	7	18			
	8	26			
	9	13			
	10	7			
5. REMOVE TOOL COVER	1	49		Watched video requested hold requested replay	
	2	73			
	3	78		Requested replay	received assistance
	4	22			
	5	20			
	6	59		Combined with next task subject commented that pause in VIMAD seemed to be in the wrong place, you pull cable and unlatch it, then hold the cable, exerting pressure, while you asked the machine to continue.	
	7	20			
	8	105			
	9	13			
	10	11			
6. STOW TOOL COVER	1	38			"Stow it where?"
	2	35			
	3	63		Egressed foot restraint to stow cover, rt hand on cover, left hand to stabilize concern, "I don't know how well this is on here"	
	4	54			
	5	46			

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
6. (Cont'd)	6			See previous task	
	7	16			
	8	44			
	9	11	Improperly stowed, Velcro pads not engaged		
	10	56			
7. INGRESS FOOT RESTRAINT	1			Ignored, still in PFR	
	2			NA	
	3	20			
	4			NA	
	5			Part of previous task	
	6			NA	
	7			Ignored, still in PFR	
	8			Ignored, still in PFR	
	9			Ignored, still in PFR	
	10			NA	
8. LOCATE SEAL VERIFICATION TOOL ON MAP	1			Map showed two tools	
	2	5			
	3	13			
	4			NA	
	5			NA	
	6			NA	
	7	12			
	8	15			
	9	13			
	10			NA	
9. TETHER SEAL VERIFICATION TOOL - LEFT ORS TETHER RING	1	138	Missed tether loop	VIMAD shows two tools	requested hold requested replay requested hold

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
9. (Cont'd)	2	105		Two tool on map?	
	3	57	Missed instruction on left tether loop		
	4	7			
	5			NA, skipped	
	6			NA, skipped	
	7	62	Tried to use wrist tether		Corrected by TD
	8	69			
	9	29			
	10			NA, skipped	
10. CHECK PRESSURE ON GAUGE	1	31		Strange gage, bent needle reads zero	
	2	23			
	3	8			
	4	7			
	5			NA, skipped	
	6			NA, skipped	
	7	16			
	8	15			
	9	3			
	10			NA, skipped	
11. RESTOW AND UNTETHER SEAL VERIFICATION TOOL	1	63		Power loss on video stowed without video untethered after watching video	
	2	59			
	3	14			
	4	20			
	5			NA, skipped	
	6			NA, skipped	
	7	19			
	8	24			
	9	18			
	10			NA, skipped	

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
12. LOCATE WIRE CLIPPERS ON TOOL MAP	1			NA	Verbal description needed
	2	30			
	3	18			
	4			NA	
	5			NA, skipped	
	6			NA, skipped	
	7	10		NA, skipped	
	8	10			
	9	12			
	10			NA, skipped	
13. TETHER WIRE CLIPPERS WRIST TETHER RING	1	12			
	2	49			
	3	34	Diver had to release tether which had been tied to itself		
	4	66			
	5			NA, skipped	
	6			NA, skipped	
	7	25			Requested pause
	8	40			
	9	17			
	10			NA, skipped	
14. CLIP AND BEND AWAY SAFETY WIRES WIRES ON DUST COVER	1	45			Leslie added instruction
	2	33			
	3	43			
	5			NA, skipped	
	6			NA, skipped	
	7	25			
	8				
	9	19			
	10			NA, skipped	

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
15. RESTOW AND UNTETHER WIRE CLIPPERS	1	16			
	2	37			
	3	19			
	4	39			
	5			NA, skipped	
	6			NA, skipped	
	7	19			
	8	13			
	9	18			
	10			NA, skipped	
16. LOCATE DUST CAP REMOVAL TOOL ON MAP	1			NA	
	2	15			
	3	6			
	4			NA	
	5			NA	
	6			NA	
	7	8			
	8	9			
	9			NA	
	10			NA	
17. WRIST TETHER DUST CAP REMOVAL TOOL	1			Data loss due to tape switch	
	2	31			
	3	12			
	4	49			
	5	17			
	6			NA	
	7	15			
	8	10			
	9	13			
	10			NA	

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
18. REMOVE DUST CAP WITH 6-3/4 TURNS CCW	1				
	2	179		See previous task required extension	
	3	91			
	4	299			
	5	91			
	6	160		Subject liked VIMAD stops and continue commands	
	7	75			
	8	38			
	9	50			
	10	53			
19. RESTOW AND UNTETHER DUST CAP REMOVAL TOOL	1	16			
	2	28			
	3	52			
	4	70			
	5	114		Cap stowed in trash bag per VIMAD	
	6			NA	
	7	12			
	8	14			
	9	31			
	10	17		Cap in trash bag	
20. LOCATE BALL VALVE ON TOOL MAP	1				
	2	9			
	3	22			Requested replay
	4			NA	
	5			NA	
	6			NA	
	7	9			
	8	7			
	9	1			
	10			NA	

TASK	RUN/TIME #/(SEC)	ERRORS	COMMENTS	HELP
21. TETHER BOTH BALL VALVE CAPS TO RIGHT ORS TETHER RING	1 220	Did not attach both caps to rt. tether	Trouble right tether loop text truncated, too much chatter	Asked tape to procede after tethering one end
	2 91			
	3 104			Warned about safety tab; reminded to attach both to right tether; reminded of procedure
	4 139		interruption to adjust foot restraint	
	5 39	Tried to use wrist tether		
	6		NA	
	7 57			
	8 88			
	9 78	Missed rt. tether loop		Reminded of tether loop; asked about tether assignment then rejected offer of reply
	10 26			
22. UNSTOW BALL VALVE AND REMOVE SMALL CAP	1 50			Warned about safety tab; subject asked if cap is removed by unscrewing
	2 50			
	3 107			
	4 35			
	5 39			
	6		NA	
	7 37			
	8 84			
	9		Incomplete	
	10 63			

TASK	RUN/TIME #/(SEC)	ERRORS	COMMENTS	HELP
23. INSTALL BALL VALVE ON UN-COVERED PORT - ST/CW-MAKING SURE SAFETY CATCH ENGAGES	1 239	Attempted to cross thread	Uncertain when valve was properly engaged, did not know to check	Asked if valve was threading correctly; diver had to complete installation (extra min.)
	2 140	Attempted to cross thread		Cross threading corrected; diver checked safety, then completed task.
	3 123			Diver engaged safety; diver checked then completed engagement
	4 200	Attempted to cross thread	Did not know how to check engagement; subject verified safety engaged;	
	5 25			
	6 70		Subject commented that tape should not require another "continue" after the tether slide. If you have already said "continue" to get it to start into the next subset of procedures, you obviously are ready for it to proceed and should not have to give another "continue" command after the tether slide.	
	7 79		Safety did not engage, hardware problem	Asked for number of turns; asked h to verify safety subject; was aske
	8 77			

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
23. (Cont'd)					to check installation by back driving it; the safety catch had not engaged, subject retightened ball valve and went on to next step.
	9			Run terminated	
	10	163			
24. CLOSE BALL VALVE RAISE GOLD HANDLE	1	5			
	2	12			
	3	20			
	4	4			
	5	6			
	6			Insert used	
	7	11			
	8	12			
	9			NA	
	10	6			
25. REMOVE SILVER CAP FROM END OF BALL VALVE	1	20			
	2	40			
	3	43			
	4	24			
	5	34			
	6			NA	
	7	17			
	8	25			
	9			NA	
	10	34		Cap placed in trash	

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
26. TETHER SEAL VERIFICATION TOO (VERBAL INSTRUCTIONS ON WHICH TETHERS TO USE)	1	57	Tethered wrong end subject corrected later		Requested hold "which end do they want?"
	2	63			
	3	89	Attempted to tether wrong end		Requested hold after verbal instructions to tether first cap
				TC instructed subject to use wrist tether to save time	
	5	62			
	6			NA	
	7	38			
	8	59			
	9			NA	
	10	54			
27. REMOVE RED CAP. PUT TETHERED CAP TO LEFT OF TOOL TRAY	1	45			Task repeated by Leslie
	2	26			
	3	42			
	4			NA	
	5	20			
	6			NA	
	7	33			
	8	55			
	9			NA	
	10			Inadequate video to retrieve data	
28. INSTALL TOOL ON BALL VALVE - 6T CW UNTIL TIGHT	1	57			
	2	42			Subject asked about tool orientation during installation
	3	50			

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
28. (Cont'd)	4	140		End of run	
	5	63			
	6			NA	
	7	41			
	8	29			
	9			NA	
	10			Inadequate video	
29. RELEASE SAFETY	1	40			
	2	30		Time lost due to tool freedom to rotate	
	3	7			
	4			NA	
	5	24			
	6			NA	
	7	13			
	8	7			
	9			NA	
	10			Inadequate video	
30. TURN GREEN KNOB CCW AS FAR AS POSSIBLE	1			NA	
	2	13			
	3	14			
	4			NA	
	5	7			
	6			NA	
	7	8			
	8	7			
	9			NA	
	10			Inadequate video	
31. CHECK PRESSURE GAUGE	1	13			
	2	7			
	3	5			
	4			NA	
	5	0			

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
31. (Cont'd)	6			NA	
	7	5			
	8	13			
	9			NA	
	10			Inadequate video	
32. OPEN BALL VALVE. PULL GOLD HANDLE DOWN	1	13		Pulling gold handle down and opening ball valve appear to be two different tasks	
	2	7			
	3	12			
	4			NA	
	5	7			
	6			NA	
	7	9			
	8	9			
	9			NA	
	10			Inadequate video	
33. CHECK PRESSURE GAUGE	1	5			
	2	4			
	3	10			
	4			NA	
	5	2			
	6			NA	
	7	3			
	8	2			
	9			NA	
	10	6			
34. CLOSE BALL VALVE. RAISE GOLD HANDLE	1	17		Close ball valve and raise gold handle - sounds like two different operations	
	2	7			
	3	10			Subject asked for

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
34. (Con'td)					clarification as to which handle is used, green or gold
	4			NA	
	5	15			
	6			NA	
	7	5			
	8	4			
	9			NA	
	10	12			
35. TURN GREEN KNOB CW TO ORIGINAL POSITION	1	5			
	2	21			
	3	31	Safety not engaged	Combined with next step	Subject was asked to check engagement of safety
	4			NA	
	5	13			
	6			NA	
	7	10			
	8	15			
	9			NA	
	10			Inadequate video	
36. REENGAGE SAFETY. TURN BOLT CW/90^0.	1	18			
	2			NA	
	3			See previous task	
	4			NA	
	5	29			
	6			NA	
	7			Part of previous task	
	8	7			
	9			NA	
	10			Inadequate video	

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
37. REMOVE SEAL VERIFICATION TOOL - 6R CCW	1	50			
	2	39			
	3	36			
	4			NA	
	5	24			
	6			NA	
	7	25			
	8	38			
	9			NA	
	10			Spanner wrench used	
38. REPLACE END CAP, RESTOW AND UNTETHER	1	31			
	2	97		Tether interfered with cap	
	3	36			
	4			NA	
	5	77			
	6			NA	
	7	56			
	8	85			
	9			NA	
	10			NA	
39. LOWER THEN RAISE GOLD HANDLE ON BALL VALVE	1	11			
	2	16			
	3	18			
	4			NA	
	5	17	Subject forgot step		Reminded of step by Leslie
	6			NA	
	7	17			
	8	7			
	9			NA	
	10			NA	

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
40. LOCATE NUT RETAINER TOOL ON TOOL MAP	1			NA	
	2	16			
	3	3			
	4			NA	
	5			NA	
	6			NA	
	7	10			
	8	10			
	9			NA	
	10			NA	
41. TETHER NUT RETAINER TOOL TO WRIST TETHER RING	1	43		Helpful if tape is stopped when text is still up so it can be referred to	
	2	28			
	3	33			
	4			NA	
	5	12			
	6			NA	
	7	6			
	8	7	Subject erroneously instructed to attach both tethers during this step. Times have been separated as best as possible.		
	9			NA	
	10	53	Rt ORS tether used		
42. UNSTOW AND TETHER END CAP TO LEFT ORS TETHER RING	1	34		Subject could not read all text, but could tell from video what to do	
	2	37			

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
42. (Cont'd)	3	38	Subject did not put tether thru left tether ring		
	4			NA	
	5	34			
	6			NA	
	7	21			
	8	16			
	9			NA	
	10	4			
43. REMOVE PROTECTIVE CAP	1	18			
	2	30			
	3	31			Additional verbal instruction
	4			NA	
	5	14			
	6			NA	
	7	85		Audio helpful, but text should say "By rotating it so many turns, etc . . ."	
	8	25			
	9			NA	
	10	12			
44. SLIDE RED COLLAR AWAY FROM KNOB	1	8			
	2	11			
	3	29			
	4			NA	
	5	4			
	6			NA	
	7	10			
	8	8			
	9			NA	
	10	4			

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
45. THREAD RED COLLAR ONTO BALL VALVE-4 1/2 T CW	1	35			
	2	47			
	3			Combined with previous step	
	4			NA	
	5	21			
	6			NA	
	7	18			
	8	23			
	9			NA	
	10	36			
46. OPEN BALL VALVE, PULL GOLD HANDLE DOWN	1	7			
	2	12			
	3	26			
	4			NA	
	5	5			
	6			NA	
	7	10			
	8				
	9			NA	
	10	4			
47. INSERT TOOL SHAFT THRU BALL VALVE	1	26			Added instruction on turning handle to seat tool on nut
	2	23			
	3	12			
	4			NA	
	5	13			
	6			NA	
	7	14			
	8	14			
	9			NA	
	10	7			

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
48. MAKE 6T CCW AND RETRACT TOOL SHAFT. IMPORTANT TO COUNT TURNS HERE	1	81		should reference to turn count	
	2	91	instructional error to proceed to next prior to retracting tool shaft		
	3	86			instruction given to rotate tool to seat on nut and to count turns for verification
	4			NA	
	5	27			
	6			NA	
	7	142			subject not clear on what should happen when tool is retracted, expected it to come free, corrected by TC
	8	30			
	9			NA	
	10	40			subject asked for verification of turn count
49. CLOSE BALL VALVE RAISE GOLD HANDLE	1	8			
	2	4			
	3	12			
	4			NA	
	5	4			
	6			NA	
	7	5			
	8	9			
	9			NA	
	10	2			

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
50. REMOVE TOOL 4-1/2 TURNS CCW ON RED COLLAR	1	50			
	2	33			
	3	18			
	4			NA	
	5	13			
	6			NA	
	7	19			
	8	18			
	9			NA	
	10	14			
51. CHECK TOOL END FOR NUT AND CAP	1	20			
	2	4			
	3	9			
	4			NA	
	5	5			
	6			NA	
	7	2			
	8	5			
	9			NA	
	10	2			
52. REPLACE TOOL CAP	1	35			
	2	50			
	3	45			
	4			NA	
	5	20			
	6			NA	
	7	31			
	8	23			
	9			NA	
	10	35			subject reminded of task by test conductor

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
53. UNTETHER CAP	1	25			
	2	81		combined with next step	
	3	40			
	4			NA	
	5	6			
	6			NA	
	7	6			
	8	8	experimenter error in instructing subject to remove both tethers prior to restow, no effect on time		
	9			NA	
	10			NA	
54. RESTOW AND UNTETHER TOOL	1	33			
	2			see above	
	3			done with prior step	
	4			NA	
	5	19			
	6			NA	
	7	9			
	8	16			
	9			NA	
	10	38			
55. LOCATE MULTI-PURPOSE TOOL ON TOOL MAP	1			NA	
	2	7			
	3	6			
	4			NA	
	5			NA	
	6			NA	
	7	8			
	8	13			
	9			NA	
	10			NA	

TASK	RUN #	TIME (SEC)	ERRORS	COMMENTS	HELP
56. TETHER MULTI-PURPOSE TOOL CAP TO LEFT ORS TETHER RING	1	42			subject questioned location of cap, was told end opposite hose
	2	33			
	3	37	tether not routed through tether loop		
	4			NA	
	5	41			additional instruction on which tether to use
	6			NA	
	7	20		NA	
	8	42			
	9			NA	
	10	28			
57. REMOVE TOOL CAP	1	24			
	2	43			
	3	46			
	4			NA	
	5	22			
	6			NA	
	7	30			
	8	55			
	9			NA	
	10	11			
58. SLIDE LARGE BLUE COLLAR AWAY FROM TOOL'S HOSE	1			combined with next two steps	
	2	31			
	3	22			
	4			NA	
	5	4			
	6			NA	

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
58. (Cont'd)	7	6			
	8	7			
	9			NA	
	10	7			
59. THREAD COLLAR ONTO BALL VALVE 4-1/2 T CW OR UNTIL TIGHT	1			combined with next step	
	2	45	erroneous instruction given to insert through ball valve		
	3	23	subject erroneously reported that collar was tight, diver corrected		
	4			NA	
	5	19			
	6			NA	
	7	41			
	8	28			
	9			NA	
	10	40		hose came off, time loss accounted for	
60. OPEN BALL VALVE, PULL PULL GOLD HANDLE DOWN	1	90		Includes two previous steps	
	2	10			
	3	25			
	4		NA		
	5	4			
	6			NA	
	7	3			
	8	2			
	9			NA	
	10	6	attempted to insert tool before opening valve		

TASK	RUN/TIME #	(SEC)	ERRORS	COMMENTS	HELP
61. INSERT TOOL SHAFT THRU BALL VALVE UNTIL CONTACT IS MADE/ FELT	1	55		color display would be helpful	Leslie volunteered that this was a sensitive step; make sure red tabs do not contact ring
	2	17			
	3	106		subject stopped short, reporting contact; requested to push in farther by TC inadvertently pushed to far corrected by diver	
	4			NA	
	5	7			
	6			NA	
	7	8			
	8	12			
	9			NA	
	10	3			
62. ROTATE KNURLED HANDLE 3-1/2 T CW OR UNITL TIGHT	1	119		some confusion about relationship between red tabs and ring	
	2	80		time lost due to ring turning with red tabs	
	3	32			
	4			NA	
	5	17			
	6			NA	
	7	115		threads did not seat initially subject applied pressure while turning, successful	

TASK	RUN/TIME #/(SEC)		ERRORS	COMMENTS	HELP
62. (Cont'd)	8				
	9			NA	
	10	43			
63. PUSH KNURLED HANDLE TO ENGATE RED TABS OVER TOOL LIP	1	200		hardware failure, tabs would not engage, no conceptual problems with ED, but suggested branching to solve problems	
	1	10			
	3	4			
	4			NA	
	5	4			
	6			NA	
	7	2			
	8	2			
	9			NA	
	10	6			

"PROCEDURE COMPLETE"

APPENDIX C: Transcripts of Simulation Master Tapes

This section includes the transcripts of all neutral buoyancy test master tapes analyzed in detail in the preparation of this report.

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HMD/ELECTRONIC DOCUMENTATION TEST TRANSCRIPT

TEST # 1 . USAF Subject: Untrained, With ED

TAPE #3 - 2/5/87 P.M.

TAPE COUNTER	EVENT	TIME
0045	Subject at top of steps Ready for arm weight	
0326	Start pressurization	
0398	Pressure 3.5 PSI Start down stairs	
0645	Helmet submerges	13:54:00
0755	Switch to underwater camera. Subject on lower platform being ballasted. Very murky water.	
1195	Ballasting complete. Starting translation to ORS.	14:01:00
1260	Start foot restraint ingress	
1300	Bumped mirror ingressing foot restraints.	
1400	Readjusting foot restraint 12" lower	14:05:00

TAPE #3 - 2/5/87 P.M.
Continued

TAPE COUNTER	EVENT	TIME
1560	Channel on foot restraint base broken	
1893	Subject returns to foot restraint	
1964	<u>GRASP HAND KNOB</u> o Ignored because already in restraint	14:14:00
1970	<u>FOLD BACK THERMAL COVERS</u>	14:14:15 - 14:15:11
2030	<u>INGRESS FOOT RESTRAINT</u> o Ignored - already in restraint	14:15:23
2040	<u>UNLATCH AND STOW LANDING BRACE</u>	14:13:29 - 14:15:46
2055	<u>REMOVE TOOL COVER</u> o Requested replay of tape sequence o Also received verbal assistance from test conductor	14:15:47 - 14:17:05

TAPE #3 - 2/5/87 P.M.

Continued

TAPE COUNTER	EVENT	TIME
2130	STOW TOOL COVER o Did egress restraints to stow cover. Used right hand on cover, left hand to stabilize	14:17:06 - 14:18:09
2190	INGRESS FOOT RESTRAINTS	14:18:10 - 14:10:30
2195	LOCATE SEAL VERIFICATION TOOL	14:18:31 - 14:18:44
2220	TETHER SEAL VERIFICATION TOOL o Subject indicated he did not understand map; therefore did not know where tool was located. o Requested replay of map. Map indication of 2 tools confused subject	14:18:45 - 14:19:57
2285	TETHER SEAL VERIFICATION TOOL o Subject missed instruction to put left ORS tether through loop at left.	14:18:58 - 14:20:55

TAPE #3 - 2/5/87 P.M.
Continued

TAPE COUNTER	EVENT	TIME
2340	CHECK PRESSURE ON GAUGE	14:21:05 - 14:21:13
2350	RESTOW AND UNTETHER	14:21:14 - 14:21:28
2365	LOCATE WIRE CLIPPERS	14:21:29 - 14:21:47
2380	TETHER WIRE CLIPPERS WITH WRIST TETHER o 14 seconds lost while diver released wrist tether which had inadvertantly been left installed upon itself.	14:21:48 - 14:22:22
2410	CLIP AND BEND AWAY SAFETY WIRES ON DUST COVER	14:22:23 - 14:23:06
2435	RESTOW AND UNTETHER WIRE CLIPPERS	14:23:07 - 14:23:26
2465	LOCATE DUST CAP REMOVAL TOOL	14:23:27 - 14:23:33
2473	WRIST TETHER DUST CAP REMOVAL TOOL	14:23:39 - 14:23:46

TAPE #3 - 2/5/87 P.M.

Continued

TAPE COUNTER	EVENT	TIME
2484	REMOVE DUST CAP WITH 6-3/4 TURNS CCW	14:23:47 - 14:25:18
2561	RESTOW REMOVAL TOOL WITH DUST CAP AND UNTETHER	14:25:19 - 14:26:11
2606	LOCATE BALL VALVE o Subject required replay of map to find ball valve	14:26:12 - 14:26:34
2625	TETHER 2 BALL VALVE CAPS TO RIGHT ORS TETHER o T. C. gave verbal warning about safety tab	14:26:35 - 14:28:19
2707	UNSTOW BALL VALVE AND REMOVE SMALL CAP o Subject asked if small cap is removed by unscrewing	14:28:20 - 14:30:07
2795	INSTALL BALL VALVE ON UNCOVERED PORT - 5T/CW o Safety catch did not engage. Diver secured it.	14:30:08 - 14:32:11
2895	CLOSE BALL VALVE RAISE GOLD HANDLE	14:32:12 - 14:32:32

TAPE #3 - 2/5/87 P.M.

Continued

TAPE COUNTER	EVENT	TIME
2910	REMOVE SILVER CAP FROM END OF BALL VALVE	14:32:33 - 14:33:16
2945	TETHER SEAL VERIFICATION TOOL o Subject requested hold after verbal instruction to tether first cap o When subject retrieved tether and prepared to attach first tether ring, he remembered wrong end.	14:33:17 - 14:34:46
3015	REMOVE RED CAP. PUT TETHERED CAP TO LEFT OF TOOL TRAY	14:34:47 - 14:35:29
3045	INSTALL TOOL ON BALL VALVE. 6T CW UNTIL TIGHT	14:35:30 - 14:36:20
3086	RELEASE SAFETY	14:36:21 - 14:36:28
3090	TURN GREEN KNOB CCW AS FAR AS POSSIBLE	14:36:29 - 14:36:43
3105	CHECK PRESSURE GAUGE	14:36:44 - 14:36:49
3110	OPEN BALL VALVE PULL GOLD HANDLE DOWN	14:36:50 - 14:37:02

TAPE #3 - 2/5/87 P.M.

Continued

TAPE COUNTER	EVENT	TIME
3120	CHECK PRESSURE GAUGE	14:37:03 - 14:37:13
3130	CLOSE BALL VALVE RAISE GOLD HANDLE o Subject asked for clarification - "was it the green handle or the gold handle?"	14:37:14 - 14:37:24
3135	TURN GREEN KNOB CW TO ORIGINAL POSITION o Subject was asked to double check safety engaged - it was not.	14:37:25 - 14:37:56
3150	REMOVE SEAL VERIFICATION TOOL	14:37:57 - 14:38:33
3190	REPLACE END CAP. RESTOW AND UNTETHER	14:38:34 - 14:39:53
3250	LOWER - THEN RAISE GOLD HANDLE ON BALL VALVE	14:39:54 - 14:40:12
3260	LOCATE NUT RETAINER TOOL	14:40:13 - 14:40:16
3265	TETHER NUT RETAINER TOOL TO WRIST TETHER	14:40:17 - 14:40:50

TAPE #3 - 2/5/87 P.M.
Continued

TAPE COUNTER	EVENT	TIME
3290	UNSTOW AND TETHER END CAP TO LEFT ORS TETHER	14:40:51 - 14:41:29
	o subject did not put tether thru left tether ring	
3320	REMOVE PROTECTIVE CAP	14:41:30 - 14:42:01
	o subject required additional verbal clarification of how to remove cap	
3345	SLIDE RED COLLAR AWAY FROM KNOB	14:42:02 - 14:42:31
	Thread read collar onto ball valve - 4-1/2 T CW	combined with previous step
3365	OPEN BALL VALVE PULL GOLD HANDLE DOWN	14:42:32 - 14:42:58
3385	INSERT TOOL SHAFT THRU BALL VALVE	14:42:59 - 14:43:11
3390	MAKE 6T CCW RETRACT TOOL SHAFT	14:43:12 - 14:44:38

TAPE #3 - 2/5/87 P.M.

Continued

TAPE COUNTER	EVENT	TIME
	o T. C. volunteered need to rotate handle a bit to make sure tool is seated on nut. o T. C. also added that it is important to count turns as there is no other way of verifying that nut is loose.	
3455	CLOSE BALL VALVE RAISE GOLD HANDLE	14:44:39 - 14:44:51
3465	REMOVE TOOL 4 1/2 T CCW ON RED COLLAR	14:44:52 - 14:45:10
3480	CHECK END OF TOOL FOR NUT	14:45:11 - 14:45:20
3490	REPLACE TOOL PROTECTIVE CAP	14:45:21 - 14:46:06
3520	UNTETHER CAP	14:46:07 - 14:46:47
	RESTOW AND UNTETHER TOOL	Accomplished jointly with previous task

TAPE #3 - 2/5/87 P.M.
Continued

TAPE COUNTER	EVENT	TIME
3545	LOCATE MULTIPURPOSE TOOL	14:46:48 - 14:46:54
3550	TETHER MULTIPURPOSE TOOL CAP TO LEFT ORS TETHER o Subject did not route tether thru left tether loop	14:46:55 - 14:47:32
3580	REMOVE TOOL CAP	14:47:33 - 14:48:19
3583	END OF TAPE	

TAPE #3 - 2/5/87 P.M.

Continued

TAPE COUNTER	EVENT	TIME
	CONTINUE WITH SMS NB 8701 TAPE #2 (2/5/87)	
0050	SLIDE LARGE BLUE COLLAR AWAY FROM TOOL'S HOSE	14:48:20 - 14:48:42
0085	THREAD COLLAR ONTO BALL VALVE 4 1/2 T CW OR TIGHT	14:48:43 - 14:49:05
	o Subject erroneously reported that collar was tight. Corrected by diver.	
0125	OPEN BALL VALVE PULL GOLD HANDLE DOWN	14:49:07 - 14:49:32
0163	INSERT TOOL SHAFT THRU BALL VALVE UNTIL CONTACT	14:49:48 - 14:51:34
	o Subject stopped short, reporting contact. o Requested to push in fartherby test conductor. o Inadvertently pushed too far, corrected by diver.	
0345	ROTATE KNURLED HANDLE 3 1/2 T CW OR TIGHT	14:51:35 - 14:52:07

TAPE #3 - 2/5/87 P.M.

Continued

TAPE COUNTER	EVENT	TIME
	CONTINUE WITH SMS NB 8701 TAPE #2 (2/5/87) (Cont'd)	
0390	PUSH TO ENGAGE RED TABS OVER LIP	14:52:08 - 14:52:12
	PROCEDURE COMPLETE	

HMD/ELECTRONIC DOCUMENTATION TEST TRANSCRIPT
TEST # ___. USAF Subject: ORS-Trained, No ED

TAPE #8 - 2/6/87 A.M.

TAPE COUNTER	EVENT	TIME
0032	Topside, Subject in donning station	8:41:30
0210	Out of donning station	
0545	Starting to pressurize	
0615	Starting down steps	
0860	Starting to lower platform	
1100	Switch to underwater camera. Water murky	
1300	Divers transfer subject to ORS work station	
1374	Subject arrives at ORS Workstation. Thermal blanket hardware in background	
1440	Subject reports "in foot restraints. Foot restraint height ok, but lower than last time by 5-6 inches."	
1550	Good rear shot of subject in ORS Workstation	
1571	Test begins. "OK - Let's Go For It"	9:02:03
1631	Thermal Blankets Removed	9:03:01
	o Landing bace was was unlatched and stowed in approximately 3 seconds before side panels were folded back.	
1646	Tool Cover Stowed	9:03:34
	o Good whole body shot of subject exiting foot restraints to stow cover	
1710	Foot Restraints Ingressed	9:04:20
	o Subject skipped seal verification tool pressure check	
	o Subject skipped simulated safety wire CVT	
1775	Tether Attached to Dusp Cap Removel Tool	9:04:37

1815	Dust Cap Removed	9:06:08
1863	Removal Tool And CAp Stowed	0:06:50
	o Cap stowed in trash bag - subject was following Honeywell procedure.	
1965	2 Ball Valve Caps Tethered To Right ORS Tether	9:08:44
	o T.C. reminded subject of procedure - he had used wrist tether	
2001	Small Cap Removed From Ball Valve	9:09:23
2118	Ball Valve Installed On Uncovered Port	9:11:28
	o Subject verified safety catch properly engaged	
2122	Ball Valve Closed	9:11:34
2151	Silver CAp Removed From End Of Ball Valve	9:12:08
2209	Tether Seal Verification Tool	9:13:10
2228	Red Cap Removed From Seal Verification Tool	9:13:30
2281	Seal Verification Tool Installed On Ball Valve	9:14:33
2304	Safety Released	9:14:57
2309	Green Knob Rotated Fully Open	9:15:04
2311	Pressure Checked	9:15:04
2315	Ball Valve Opened	9:15:11
2316	Pressure Checked	9:15:13
2318	Ball Valve Closed	9:15:28
2339	Green Knob Turned CW Original Position	9:15:41
2365	Safety Bolt Reengaged	9:16:10
2383	Seal Verification Tool Removed	9:16:34
2451	End Cap Replaced Restowed And Untethered	9:17:51
2465	Ball Valve Vented By Lowering, Then Raising Gold Handle	9:18:08
	o Subject forgot this step, was reminded by T.C. (step may not be in VIMAD procedures on which he was trained)	

2475	Nut Retainer Tool Tethered To Wrist	9:18:20
2505	Tool Unstowed, End CAp Tethered To Left ORS Tether	9:18:54
2515	Protective Cap Removed	8:19:08
2519	Red Collar Slid Away From Knob	9:19:12
2537	Red Collar Threaded Onto Ball Valve	9:19:33
2539	Ball Valve Opened	9:19:38
2552	Tool Shaft Inserted Through Ball Valve	9:19:51
2572	Nut Released And Tool Retracted	9:20:18
2576	Ball Valve Closed	9:20:22
2588	Tool Removed	9:20:35
2591	Nut Verified	9:20:40
2608	Tool Cap Replaced	9:21:00
2613	Untether Cap	9:21:06
2630	Tool Restowed And Untethered	9:21:25
2663	Multipurpose Tool CAp Tethered To Left ORS Tether	9:22:06
	o Subject requested and received instructions on which tether to use.	
2681	Tool Cap Removed	9:22:28
2684	Blue Collar Slid Away From Hose End	9:22:32
2700	Tool Collar Installed On Ball Valve	9:22:51
2703	Ball Valve Opened	9:22:55
2709	Tool Shaft Inserted Until Contact	9:23:02
2724	Knurled Handle Rotated CW Until Tight	9:23:19
2726	Red Tabs Pushed To Engage Position	9:23:23
2760	Subject begins to reconfigure ORS, since second subject was not ready.	
3385	Start pressurizing next subject video still shows first subject reconfiguring ORS	:30:00

3420	Subject 2 pressurized	9:38:38
3540	First subject reinstalls thermal curtains	
3575	ORS Reconfiguration complete	9:40:00
3600	First subject practices foot restraint ingress/egress	9:43:10
3630	End of Tape	

HMD/ELECTRONIC DOCUMENTATION TEST TRANSCRIPT

TEST # 1 . USAF Subject: ED Run With VIMAD

TAPE #10 - 2/6/87 A.M.

TAPE COUNTER	EVENT	TIME
0083	Tape begins. LMSC diver is reconfiguring ORS	
0304	Reconfiguration complete, LMSC diver gives thumbs up	10:38:24
0300	Task starts, using VIMAD procedure	10:38:24
0310	Task 1: Foldback Thermal Curtains	10:38:38 - 10:30:24
0419	Task 2: Release Tool Supports	10:39:25 - 10:40:10
0470	Task 3: Remove and stow tool box access cover	10:40:11 - 10:41:10
	o Subject commented that pause in the VIMAD tape seemed to be in the wrong page - you pull the cable and unlatch it, and then you have to hold the cable, exerting pressure, while you asked the machine to continue.	
0590	o Subject commented he can see but can't read the text, because of the size, primarily and the scratches.	
	o Subject like the steps, as opposed to the Lockheed tape telling you step by step what to do.	

0616 Task 4: <u>Remove dust cap</u> 10:41:48 - 10:44:28

- Subject commented that he likes the fact that it automatically stops after each step, and you have to tell it to continue

0818 Task 5: <u>Install Ball Valve Moving</u> 10:44:35 - 10:45:45

- Subject commented that tape should not require another "continue" after the title slide. If you have already said "continue" to get it to start into the next subset of procedures, you obviously are ready for it to proceed and should not have to give another "continue" command after the fifth slide.

1110 Split screen appears, showing VIMAD signal to subject as the inset, and subject at work.

1180 Concern over air leak from LTA

1236 Inset on split screen raised for athletic purposes

1365 Task 6: <u>Conduct leak check</u> 10:52:32 - 11:01:50

- Subject commented that he could not tell on tape where spanner wrench was located in tool tray.

- Also tape instructed subject to use left side tether for spanner wrench. Left side tether is still attached to seal verification tool.

Task 7: Remove Satellite Valve HEX Nut and Cap — 11:01:51 - 11:06:30

o After play through of first subtask subject asked for repeat.

(task completion corresponds to"Restow and Unthether Tool" step following use of nut retainer tool on Lockheed procedure)

2210 Video inset went black - changing optical discs — 11:07

2220 Task 8: Install Multipurpose Tool — 11:07:10 - 11:10:29

o Subject missed step "place feedline to right of tool", resulting in substantial twisting of feedline when tool cover was replaced, in task 10 below.

2390 Task 9: Open Satellite Valve — 11:10:30 - 11:11:37

o Hardware does not actually operate as procedures indicate.

2455 Task 10: Configure Worksite For Reentry — 11:11:38 - 11:18:52

o Subject required assistance of diver to understand how to operate landing brace locking fenture

2813 Task completed

2820 Subject exits ORS workstation and screen goes black leaving "procedure complete" in inset. — (Good shot)

2885	Helmet surfaces. Switch to top side camera	11:20:27
2970	Discussion of leak in LTA (Jeff Robert) Subject in water on upper platform.	11:23:00
3025	Subject goes up steps. Subject in donning station.	11:25:12
	End of tape	11:27:03